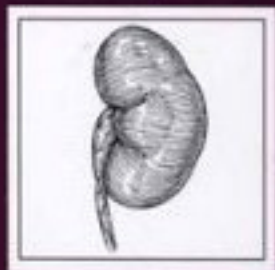


# UROLOGIC CLINICS

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Preface  
**Robotic Urologic Surgery**



Mani Menon,  
MD, FACS



Ashok K. Hemal,  
MD, MCh, FACS  
*Guest Editors*



Sakti Das,  
MD, FACS

This issue of the *Urologic Clinics of North America* may be just a bit ahead of its time. Robotic urologic surgery is in its infancy, and many of the contributions in this slim issue reflect that reality. The curious reader 5 years hence may find many of the observations in these articles to be naively innocent. However, robotic urologic surgery has been conceived (although critics will quibble about its name) and the infant is taking its first few strong steps; this is the justification behind this issue.

The development of robotics in urology has largely paralleled the development of the da Vinci Robotic System as a device and robotic prostatectomy as a surgical procedure. Thus much of this issue is devoted to these two aspects of urology. The first robotic radical prostatectomy in the United States was performed at Henrico Hospital in Virginia, followed within a matter of days by a series of cases at the Vattikuti Urology Institute, Henry Ford Hospital, Detroit, Michigan. To the Guest Editors, this was a wondrous moment. No one—least of all us—thought that the da Vinci system, which had been designed for cardiac surgery, would find its ultimate niche in urologic surgery, much less in radical prostatectomy. However, this has happened within the short span of 3 years, and robotic radical prostatectomy has established a strong foothold among

the treatment options for localized prostate cancer. It was neither great vision nor supreme insightfulness but serendipity that led us to the robot, and we are happy for that. We ask, “If serendipity can bring us so far, what more can we accomplish with a dash of vision and some good judgment?” To borrow a term from one of our illustrious leaders, people tend to “misunderestimate” the potential of robotic surgery.

**Dedication**

This issue is dedicated to Patrick C. Walsh, MD: teacher, friend, surgical visionary, and raconteur!

Mani Menon, MD, FACS  
Ashok K. Hemal, MD, MCh, FACS  
*Vattikuti Urology Institute, K9  
Henry Ford Hospital  
2799 West Grand Blvd.  
Detroit, MI 48202, USA*

Sakti Das, MD, FACS  
*1890 Via Ferrari  
Lafayette, CA 94549, USA*

*E-mail addresses:* [mmenon1@hfhs.org](mailto:mmenon1@hfhs.org)  
(M. Menon); [ahemal1@hfhs.org](mailto:ahemal1@hfhs.org) (A.K. Hemal);  
[saktidas@sbcglobal.net](mailto:saktidas@sbcglobal.net) (S. Das)

# The evolution of robotic urologic surgery

Mike Minh Nguyen, MD\*, Sakti Das, MD

*Department of Urology, School of Medicine, University of California at Davis, 4860 Y Street,  
Suite 3500, Sacramento, CA 95817, USA*

The specialty of urology historically has pioneered and embraced the use of new surgical technologies. Examples of this legacy include the development of cystoscopy, endoscopy, and laparoscopy. The advent of surgical robotics in urology is the newest horizon of this tradition. Already, robotic prostatectomy has become common, with additional applications such as robotic pyeloplasty, cystectomy, and bowel manipulation emerging from experimental status. This article reviews the history of the use of robotics in surgery, focusing on its specific application to urology.

## History

Robotic surgical technology has developed along several avenues. The type most familiar to urologists is based on the master-slave paradigm, with the surgeon directly initiating all movements of the robotic instrumentation. Examples of this type include the da Vinci Surgical System (Intuitive Surgical, Sunnyvale, California) and the Zeus Robotic Surgical System (Computer Motion, Goleta, California). In a second type of robotic surgical technology, the robot is preprogrammed to perform movements within set confines without direct guidance. These so-called “precise-path systems” include the ROBODOC hip replacement milling device (Integrated Surgical Systems, Davis, California); the Surgeon Robot for Prostatectomies, a robotic system for performing prostatectomies developed by Wickham and colleagues [1]; and the PAKY device for

percutaneous access to kidneys developed at Johns Hopkins. Other categories of surgical robots include “intern replacements,” such as the AESOP laparoscope holder (Computer Motion) and navigational/positioning systems such as the Neuromate system for brain surgery (Integrated Surgical Systems).

Master-slave technology is described more accurately as “computer-enhanced” because the instruments do not act autonomously but follow exactly the motions of a human operator. Precise-path systems more closely approximate the term *robotic* through their semiautonomous movements. Despite these semantic caveats, the authors have chosen to use “robotic” as a general term to encompass master-slave systems, precise-path systems, and other similar surgical technologies that use powered control elements to perform surgical actions either autonomously or under direct human control.

Master-slave systems in which the surgeon directly initiates movements of the robotic surgical instrumentation were developed initially in the late 1980s through a joint effort. A group of researchers at the National Aeronautics and Space Administration Ames Research Center investigating virtual reality systems collaborated with mechanical engineers at the Stanford Research Institute (SRI) interested in robotic technologies. The first effort of this combined venture was the development of a “telepresence” surgical system to improve dexterity in microscopic hand surgery. In a demonstration of this early system, end-to-end anastomosis of femoral arteries was performed in 10 rats with 100% patency [2].

From the initial SRI system for delicate microsurgery, the focus shifted to macroscopic general surgical applications. A large impetus for this change was the demonstration of laparoscopic

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\* Corresponding author.

E-mail address: [miknguyen@sbcglobal.net](mailto:miknguyen@sbcglobal.net)  
(M.M. Nguyen).

cholecystectomy in 1989 by Perissat and colleagues [3] at the Society of American Gastrointestinal Surgeons meeting in Atlanta, Georgia. The laparoscopic cholecystectomy demonstration stimulated the developers of the SRI system to realize that their robotic telemanipulators would be suited ideally for use in a similar laparoscopic fashion to perform general surgery, in addition to the originally conceived microsurgery applications [4].

Based on this expanded premise, a revised telepresence system, which included a surgeon's console and remotely controlled telemanipulators, was developed with funding from the US Department of Defense. Rather than using a laparoscopic approach, however, this system was intended initially to perform open surgery. The system came to be called the SRI Green Telepresence Surgery System after Phil Green, PhD, a researcher at SRI.

The SRI system was intended to be a battlefield surgical system for combat casualty care. The concept included a mobile, armored, operating room vehicle equipped with robotic surgical manipulators that were controlled remotely by a surgeon at a rear-area mobile surgical hospital unit. The system was designed to allow surgeons to perform temporizing surgery to control life-threatening injuries such as vascular trauma. The stabilized injured soldier then could be transported safely to a rear-area facility to undergo definitive surgery. Early studies demonstrated the system's feasibility in performing remote open trauma surgery, although operative times were 2.7 times that of open techniques [5]. Although the telepresence technology has not yet been used in combat care, eventually it led directly to the development and marketing of a commercial product, the da Vinci Surgical System.

Early in its development, the SRI Green system was used to perform urologic procedures. Bowersox and Cornum [6] used the system to perform open surgeries such as nephrectomies, cystotomy closures, and ureteral anastomoses in pigs. In addition, they remotely manipulated an endoscope in an *ex vivo* model. Despite these ambitious attempts, this early system had only four degrees of freedom, similar to standard laparoscopic instruments, and was hampered by other significant performance issues in its prototype form, keeping clinical use a future endeavor.

Across the Atlantic, another master-slave system was being developed in Germany by Schurr

and colleagues [7]. The ARTEMIS (Advanced Robotic Telemanipulator for Minimally Invasive Surgery) system included remote telemanipulators with six degrees of freedom and a three-dimensional visualization system. Although this advanced system was the first reported system with six degrees of freedom, the ARTEMIS project's funding was not renewed and it has not been developed into a commercial product [8].

Precise-path systems use a robot to control movements of an active end-effector based on preplanned or real-time criteria. The first precise-path system relevant to urologists was the Surgeon Robot for Prostatectomies, which also became the first robotic device to remove tissue from a patient when it underwent its first clinical trial in March of 1991 [9]. The system, which later was named "Probot," used a modified continuous flow resectoscope that was fitted originally with a motorized cutting blade to resect tissue. Later, this motorized blade was exchanged for a diathermy cutting loop. The resectoscope was controlled by a six-axis Unimate Puma robot constrained within a frame to ensure that resection beyond the prostate could not occur. Resection occurred in a fixed sequence of overlapping cuts to remove a conical area of tissue [10]. Overlapping cones allowed the cavity to traverse the length of the prostate. Ultrasound images obtained by the robot were used to map out the planned resection areas. The plan was then executed with the robot carrying out the designated cuts while the surgeon monitored through an interactive schematic overlay and by direct vision using video from the resectoscope.

In their initial 10 patients, the authors reported that "full or nearly full" resections were accomplished successfully with a small amount of manual resection and coagulation at the end of the procedure. Initial results reported were that "in all cases relief from outflow obstruction has been successfully achieved." Follow-up results and further clinical trials have not been published.

Additional development of the system at the Nanyang Technological University in Singapore led to a system called the URobot, which has been developed experimentally for an expanded number of applications, including robotic laser prostate resection [11], robotic prostate biopsy, and robotic brachytherapy seed instillation [12]. From this research, a commercial prototype named the Surgeon Programmable Urological Device (SPUD) underwent development in collaboration with Dornier Asia Medical Systems. Clinical trials

reportedly had commenced in 1998 using the SPUD system in Singapore, but no further information has been published.

Johns Hopkins has demonstrated another precise-path system, a robotically controlled device for percutaneous access to the kidney. The PAKY device incorporates a seven-degrees-of-freedom robotic arm with a needle insertion device attached to the terminal end. The needle insertion device is attached to an additional robotic device, which allows adjustments to be made to the needle trajectory. The system has been equivalent to a manual approach for accessing the renal collecting system under fluoroscopic guidance when controlled directly by the surgeon using a joystick [13]. The authors reported plans to add CT guidance and “Smart Needle” tissue bioimpedance detection technology [14] to the PAKY device to create an autonomous precise-path system for obtaining percutaneous access.

### Commercial marketing

The ROBODOC hip replacement milling device was the first robotic surgical device marketed when it was introduced in 1992 by Integrated Medical Systems. The next device was the Automated Endoscopic System for Optimal Positioning (AESOP) created by Computer Motion. Released in 1993, the device was an intern-replacement robot that allowed hands-free automated control of the endoscope. The system also familiarized many surgeons with the feasibility of the use of robotics in laparoscopic surgery [15].

Meanwhile, Fredrick Moll, MD, licensed the commercial rights to the SRI Green Telepresence Surgery System and used this acquisition to found Intuitive Surgical Systems in 1995. After further development, a renovated master-slave clinical system was released in April 1997 in prototype form as the da Vinci surgical system. The system received US Food and Drug Administration (FDA) approval in July 2000. Unlike its progenitor, the da Vinci was intended solely for laparoscopic surgery as opposed to open surgery.

Within a year, Computer Motion released its own master-slave system, the Zeus Surgical System, which received FDA approval for limited abdominal operations in October 2001. Building on its original AESOP technology, Computer Motion added two surgeon-controlled robotic telemanipulators to complete the system. Acquisition costs for these systems are roughly \$80,000

for AESOP, \$975,000 for Zeus, and \$1 million for da Vinci [16]. In June 2003, Intuitive Surgical and Computer Motion completed a merger to combine their intellectual property and market and support product lines from both former companies.

### Current commercially available systems

#### *Automated endoscopic system for optimal positioning*

Computer Motion’s AESOP consists of a voice-controlled robotic endoscope holder with four degrees of freedom. The system initially was controlled with cumbersome hand mechanisms before progressing to foot controls and then the current voice controls [17]. The surgeon interacts with the system using a directional microphone. In addition to the advantage of a hands-free and assistant-free device, AESOP provides a stable image from which the surgeon can work. The system also has been used for telementoring, whereby a remote mentor surgeon controls the camera for the purpose of instructing and guiding the operating surgeon. The concept has been used to connect mentors in the United States to remote surgeons in other locales including Munich, Rome, Singapore, and Brazil [18–22]. Computer Motion also markets the “SOCRATES” telecollaboration system, which integrates its AESOP and Zeus systems with remote telementoring abilities.

#### *da Vinci surgical system*

The da Vinci surgical system consists of a surgeon’s computer console for surgeon interaction, a surgical cart that houses the video and lighting equipment, and a robotic tower that supports three or four robotic arms. The surgeon’s console provides the user a three-dimensional view through a binocular viewport. Interaction is through “masters” into which the surgeon inserts his or her hands. The masters allow free movement that is translated intuitively into seven degrees of freedom at the robotic instrument tips. A double lens laparoscope system is combined into a single three-dimensional binocular view by the da Vinci system. The robotic tower supports three or four robotic arms with one arm always controlling the camera. Endowrist instruments come in a wide range of types including graspers, scissors, hooks, knives, and surgical energy devices.

### *Zeus surgical system*

The Zeus surgical system consists of a surgeon's console and three separate robotic arms that are attached to the operating room table. The console is based on an open design with the surgeon interfacing with the robotic arms through control elements attached to a unit placed behind the sitting position. A monitor sits in front of the surgeon with the main laparoscopic view. Control of the AESOP camera is through voice commands. Originally, the main view was a standard two-dimensional image. Because the Zeus system uses an open architecture, different imaging systems can be implemented to add three-dimensional capability. A three-dimensional interface can thus be added using the Karl Storz Tricam three-dimensional system (Karl Storz Endoscopy-America, Culver City, California). In the initial system, the control elements were similar to standard laparoscopic instrument handles and controlled robotic instruments with only four degrees of freedom. The current system uses "Microwrist" instruments with six degrees of freedom. With the Zeus, each of the three separate robotic arms is attached to the surgical table, with one controlling the camera.

### **Applications**

Kavoussi and colleagues [23] reported on the early clinical use of robotic technology to assist during laparoscopic surgery in 1994. They used an AESOP camera arm controlled by a remote surgeon to manipulate the endoscope while performing a cholecystectomy, a varix ligation, and a bladder suspension. Standard laparoscopy was used to perform the surgery. The clinical use of fully robotic systems was initially in Europe. Cadiere and colleagues [24] used the da Vinci system to perform 146 cases between March 1997 and February 2001. The cases performed were primarily general surgery procedures but also included two prostatectomies and one varicocele ligation. No robotic-related complications were encountered and the authors believed that the system was safe, feasible, and most beneficial for the delicate microsurgery elements of procedures and for operating in constrained spaces.

In the United States, Talamini and colleagues [25] presented their early experience with the da Vinci system on surgeries performed between June 2000 and June 2001. The 211 procedures were primarily general surgery procedures, but

included 15 donor nephrectomies and six adrenal-ectomies. Generalizations from the study were that robotic surgery was feasible and that it could be performed with approximately equal efficacy and outcomes to standard laparoscopy.

Robotic systems subsequently have been used to perform a number of urologic procedures, including radical prostatectomies, nephrectomies, pyeloplasties, cystectomies, adrenalectomies, vasa-vasostomies, and pelvic floor procedures.

### **General considerations**

Robotic surgical systems, like all technologies, are a tradeoff between benefits and drawbacks. General limitations include the high costs involved in acquiring and maintaining the systems, the setup times involved, and limited access to patients. The robotic arms are somewhat constrained to a smaller field and can interfere with each other when larger movements are made. Haptic feedback is lacking and impairs the surgeon's vital ability to make intuitive decisions based on tension and texture. These drawbacks are not static, however, and will decrease as the technology matures and experience using these systems increases. Although costs are higher than standard technology, as systems become more common and competition invariably arises, one can expect these costs to come down. Setup times consistently decrease with experience as staff becomes more familiar with the equipment and steps required, as was evidenced by the decrease from 32 minutes to 17 minutes needed for port placement and robot setup in a series of robotic prostatectomies using the da Vinci system [26]. When these systems become more common, dedicated rooms prewired for computerized surgical systems with ceiling-mounted equipment will decrease setup times further and decrease the intrusion of the systems into the operating environment. Research also is continuing on incorporating haptic feedback into these systems.

The most prominent benefit of robotic surgical systems is the increased dexterity of the instruments, which allows the use of traditional surgical techniques and movements in a minimally invasive environment. The motion-scaling and tremor-filtering functions also permit more measured, precise movements for complex tasks. These benefits are most obvious when used for precise surgery in constrained spaces, such as in the pelvis for prostatectomies and in the thorax for cardiac

procedures. Robotic systems are potentially less of an advantage in procedures traversing large spaces where interference between the arms becomes more of an issue and less precise, large motions are required [27]. One practical approach to overcoming this is to perform different portions of procedures using different surgical approaches including open, standard laparoscopic, and robotic laparoscopic to capitalize on each approach's advantages [28,29].

Another frequently cited benefit of robotic systems is their advanced viewing capabilities that provide a large, stable, immersive three-dimensional image. This greatly facilitates microsurgery and has proved useful for precise maneuvers such as dissection of the neurovascular bundles during prostatectomy [30]. Additional benefit is derived from the ergonomic control stations used to interface with the systems. These stations help to decrease fatigue and strain on the surgeon. These interfaces also could allow surgeons with disabilities normally incompatible with performing surgery to continue working.

With more experience using these novel robotic systems, dramatic improvements in speed and skill can occur. Chang and colleagues [31] looked at intracorporeal knot tying using the Zeus system and found steady linear improvements in time to completion and performance scores with additional training. Similar improvements are seen in clinical case series as surgeons gain more experience [26]. It is not surprising that with robotic surgery, as with any technically challenging task, dedicated practice is necessary to achieve skill.

Telesurgery and telementoring applications are new forms of collaboration and teaching that have become more feasible with robotic surgical technology. Although the FDA currently dictates that the operating surgeon must remain in the same operating room as the patient, this legal constraint is not a technical distinction with robotic systems. Surgical expertise can therefore be transferred easily to remote locations for mentoring in an academic setting or for clinical service in an underserved or hostile environment.

Robotic surgical devices are developing rapidly within the field of urology. They enhance the surgeon's ability to perform surgery in a minimally invasive fashion and can be expected to become a standard fixture of the surgical armamentarium. Over a short period, their history is remarkable for large advances in the technological aspects of the systems and in their application by clinicians into patient care. In many respects these systems

are still at an early stage in their development and can be expected to demonstrate continued expansion of capabilities, decrease in costs, and greater ease of use in the future. Ultimately, their true value will not only be in replicating current open or standard laparoscopic techniques but also in introducing novel approaches to surgeries to improve outcomes. These approaches will be minimally invasive and more precise, and will cause less subsequent trauma to tissues and patients. Alongside targeted energy approaches and genetic therapies, robotic minimally invasive surgery will be part of the paradigm shift occurring in treating disease with greater accuracy and decreased morbidity.

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# The PAKY, HERMES, AESOP, ZEUS, and da Vinci robotic systems

Hyung L. Kim, MD<sup>a</sup>, Peter Schulam, MD, PhD<sup>b,\*</sup>

<sup>a</sup>Department of Urology, Roswell Park Cancer Institute, Elm & Carlton Streets, Buffalo, NY 14263, USA

<sup>b</sup>Department of Urology, University of California, Los Angeles, School of Medicine, Box 951738, Los Angeles, CA 92691-1739, USA

The popular conception of robots comes from works of science fiction such as *Blade Runner* and *Star Wars*. The term *robot* was first coined by Karel Capek in his 1921 play *Rossums Universal Robots*. “Robot” is the Czech word for “industrial worker,” and in the play, motorized automatons with artificial intelligence were created to serve humans. Isaac Asimov, another popular science fiction writer, was the first person to use the term *robotics* to refer to the technology of robots. He predicted the rise of a pervasive robotic industry.

Even as robots have become commonplace in science fiction, more practical versions of robots have become an integral part of the manufacturing industry. In manufacturing, robots offer precision and accuracy that cannot be matched by human workers. Robots can work under extreme conditions and for extended durations. For repetitive tasks that require a high degree of consistency, they offer a clear economic advantage. The success of industrial robots has stimulated interest in applying robotics to other areas, including medicine.

A robot can be defined broadly as a mechanical device that is controlled using a computer system. The first medical specialties to use robots were neurosurgery and orthopedics [1,2]. In neurosurgery, robots were well suited for many of the surgical tasks that require accurate anatomic localization and precise surgical manipulation. Furthermore, the cranial anatomy provides relatively fixed landmarks. Robotic systems were developed for

neuronavigation, stereotactic localization, and robotic assistance [3–6]. NeuroMate (Integrated Surgical Systems, Davis, California) is a commercially available, US Food and Drug Administration (FDA)–approved robot that can help identify and direct the surgeon to the neurologic lesions. In orthopedics, the RoboDoc (Integrated Surgical Systems) was developed to assist with placement of prosthetic joints [7]. Using the RoboDoc, bone can be cut for placement of a joint prosthesis with 10 times greater accuracy than is possible manually.

Other specialties also have explored the use of robotics. Cardiac surgery was one of the first specialties to attract the interest of robotic manufacturers. Clinical trials using laparoscopic robotic systems for coronary bypass surgery are underway [8,9]. In general surgery, laparoscopic robotic systems have been used in prospective clinical trials to perform cholecystectomies [10] and Nissen funduplications [11]. The first clinical trials using robots in gynecology were for reversal of tubal ligation [11,12].

## Robots in urology

Image-guidance robotic systems can localize anatomic structures in three-dimensional (3-D) space using a series of two-dimensional (2-D) images. The NeuroMate and the RoboDoc are robotic systems that use image guidance. Two key concepts for robotic image guidance are triangulation and registration. Triangulation refers to the construction of 3-D coordinates using 2-D images. Registration refers to the integrating of landmark coordinates on the patient and reference coordinates on the robotic device to construct

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\* Corresponding author.

E-mail address: [pschulam@mednet.ucla.edu](mailto:pschulam@mednet.ucla.edu)  
(P. Schulam).

a transformation matrix. This process allows the robot to calibrate the working space and localize specific anatomic structures. **Box 1** defines robotics terminology.

The first urologic procedure performed with the assistance of a robot was a transurethral resection of the prostate (TURP) [13–15]. In 1989 a team at the Imperial College in London developed a device to automate resection of the prostate [16]. The robot had seven degrees of freedom (dof). In initial laboratory tests it was used to core out the inside of a potato. Before use in humans, a safety frame was developed that restricts the range of motion of the robot to the area of prostate resection. The frame was tested by manually maneuvering the device within the frame and performing a TURP in 30 patients [17].

After demonstrating the safety of the device, the instrument was connected to a motorized component that automated the resection based on ultrasound images. In the initial clinical trial, the device was used successfully in five patients to automate prostate resection completely before hemostasis was achieved manually [14,15]. This was the first example of off-line robotic surgery. The term *off-line* describes a robot that is preprogrammed to perform an operation without direct human interaction. This clinical trial identified the need for an alternative to transrectal ultrasound (TRUS) for accurately imaging the prostate and planning the resection.

A team of investigators at the Politecnico of Milan, Italy demonstrated the use of a robot to perform a transperineal prostate biopsy [18–20].

TRUS was used to image the prostate and external video cameras were used to record the patient's anatomy and configuration. The information from the video cameras and the TRUS were integrated to allow positioning of the biopsy needle in 3-D space. Using computer software, the surgeon chose the biopsy site on the TRUS image. The robot then positioned the needle in the prostate with an accuracy of 1 to 2 mm. This study was an important demonstration of how internal structures can be localized in 3-D space. Given the ease and accuracy of performing standard TRUS-guided prostate biopsies, however, it is unlikely that robots will provide an advantage in this procedure.

Similar robots are being investigated for obtaining percutaneous access to the renal collecting system. Again, 2-D images are used to navigate in 3-D space and target an internal structure, the renal calyx. The team at the Imperial College in London developed a robotic system with a passive manipulator to target the renal calyx [21]. Sensors on the manipulator record the position of the joints relative to the patient. To target the calyx, a computer integrates this information with data obtained by fluoroscopy. The trajectory of the needle is shown on the fluoroscopic image. The same group has described a system for calibrating the video fluoroscopy to remove distortions and achieve targeting accuracy to within 1.5 mm [21].

#### **Percutaneous access to the kidney (PAKY)**

A group at Johns Hopkins Medical Center has developed robots for obtaining percutaneous

### **Box 1. Some common robotics terminology**

**Triangulation:** generation of 3-D coordinates from a series of 2-D images.

**Registration:** use of patient landmarks (fiducial markers) and the robotic coordinate system to determine a transformation matrix. This allows the robot to navigate the target precisely.

**Degrees of freedom (dof):** number of possible translational or rotational motions at a joint. The dof of a device is the sum of the dof in all the joints.

**Master-slave device:** a two-component system with a control console and a mechanical device that performs the task.

**Off-line robots:** completely automated and preprogrammed systems that do not require human intervention.

**On-line robots:** systems that require continuous human intervention, taking advantage of human perception and judgment.

**Robots:** systems that integrate a computer and a mechanical device.

**Telesurgery:** use of master-slave devices where the master and slave components are separated physically.

renal access [22–24]. The first robot they developed has an active manipulator, a motorized arm that positions and drives the access needle. Information from sensors on the robot is integrated with calibrated images from a biplanar fluoroscopic image to target the calyx [22]. In early ex vivo experiments, the group was able to access the desired calyx in porcine kidneys with 83% accuracy. In live animal experiments, however, the robot only had 50% accuracy. The low accuracy rate was attributed to needle deflection, rib interference, and deflection of the kidney by the needle.

To reduce cost and complexity, a second robot, PAKY was developed with a passive manipulator and an active injector system (Fig. 1) [23,24]. This system mimics the standard surgical technique applied in the operating room using a C-arm. A passive arm with seven dof is mounted to the operating room table. The C-arm and needle are aligned fluoroscopically over the target calyx, highlighted by injecting air through a ureteral stent. The PAKY arm then is locked in place and the C-arm is rotated to provide a lateral view so the path of the needle and depth of insertion can be monitored. The needle is inserted by a radiolucent injection system attached to the barrel of the needle and powered by a direct current motor. The PAKY system does not require computer-based image processing for image correction and calibration. This system is currently being evaluated clinically.

## HERMES

The Hermes Operating Room Control Center (Computer Motion, Goleta, California) uses

speech recognition to control all aspects of the operating room. Rather than relying on operating room personnel, the surgeon gives commands through a headset and uses one interface to control the laparoscopic camera (white balance, zoom, gain, and photograph), light source, insufflation, printer, operating room phone, operating room lights, and position of the patient table. After a command is issued, HERMES acknowledges the command with audio feedback. HERMES can network with a range of peripherals made by different manufacturers.

Luketich and colleagues [25] evaluated the HERMES system in a randomized clinical trial. They randomized 30 patients undergoing laparoscopic antireflux surgery to HERMES-assisted or non-HERMES-assisted cases. When the HERMES system was not used, the nurses were interrupted an average of 15.3 times to make adjustments to various instruments, compared with 0.33 times when the HERMES system was used. Using a questionnaire, the mean satisfaction score for the surgeons and the operating room staff was higher in the group that used the HERMES system.

## Automated endoscopic system for optimal positioning

Conventional laparoscopic surgery is the standard for many procedures. In urology, the decrease in postoperative pain and recovery time for laparoscopic nephrectomy when compared with open surgery is well documented [26–29]. Early mechanical devices designed to facilitate laparoscopy included simple, passive devices for holding the



Fig. 1. PAKY device mounted to an operating room table with the injector positioned under a fluoroscopic C-arm. The PAKY has a passive arm with six dof and an active injector for percutaneous renal access. (Courtesy of Johns Hopkins University, Baltimore, MD; with permission.)

camera during surgery. These devices were cumbersome to use. To move the camera, the surgeon had to take his or her hand off the working instruments and position the mechanical device. Therefore, active devices were developed for positioning the camera during laparoscopy.

Automated Endoscopic System for Optimal Positioning (AESOP; Computer Motion) was the first active robotic device approved by the FDA. AESOP is a robotic arm with motorized joints that is controlled by the surgeon through the Hermes speech recognition system [30]. Endo-Assist (Armstrong Health Care, High Wycombe, United Kingdom) is a similar device, but the arm is controlled by the surgeon's head movements [31,32]. AESOP and EndoAssist give the operating surgeon full and rapid control of the camera. These devices have paved the way for master-slave devices, which control not only the camera but the surgical instruments as well.

### **ZEUS and da Vinci**

A master-slave device is a two-component system consisting of a control console and a mechanical device that performs the task. Robotically assisted surgery can be performed using master-slave devices to overcome some of the limitations of laparoscopy while maintaining the advantages of minimally invasive surgery. Although laparoscopic surgery has advantages, there are several important shortcomings:

- Many techniques, such as intracorporeal suturing, are more difficult than with open surgery.
- Laparoscopic surgery is performed with a 2-D view of the surgical field.
- The surgical ports limit maneuverability and there is a loss of two dof compared with open surgery.
- With laparoscopic surgery, there is loss of tactile sensation.

The FDA has approved two master-slave devices for human use: ZEUS (Computer Motion) and da Vinci (Intuitive Surgical, Sunnyvale, California). Both systems consist of robotic arms and a surgeon's console. The robotic arms are positioned next to the patient in the operating room: two arms control the working instruments and one arm positions the camera. The surgeon sits at a console, which can be located in the same room or at a distant site. The surgeon has a view of the surgical field from the console. Hand movements at

the console are digitized and modified by a computer system that then manipulates the robotic arms in real time.

These master-slave systems provide several potential advantages over conventional laparoscopy:

- The surgeon's console provides an ergonomic environment for performing surgery. The surgeon also can make natural hand movements rather than counter-intuitive movements from uncomfortable positions, which often is required by conventional laparoscopy.
- By digitizing the surgeon's hand movements, the robotic system can filter out hand tremors and scale movements. For example, large hand movements at the surgical console are translated into small and precise movements at the operative site.
- The robotic arms can provide additional dof inside the patient's body for enhanced endoscopic dexterity. Compared with the rigid, fixed laparoscopic instruments, the robotic arms have additional joints that can reproduce more closely the movements of the human wrist.
- These systems provide 3-D views of the surgical field and therefore improve depth perception.

In June 2003, the companies that manufacture ZEUS and da Vinci merged, and the new company uses the name Intuitive Surgical, Inc. Both systems remain in clinical use, and several key differences should be noted.

The ZEUS system is an expansion of the AESOP device, originally designed for manipulating the laparoscope. The system consists of three robotic arms that are mounted to the operating room table (Fig. 2). Therefore, the robotic arms do not need to be repositioned or calibrated when the operating table is adjusted. The arm controlling the camera is the AESOP device, and is controlled by speech recognition. In the early version of the ZEUS system, the working arms controlling the surgical instruments had five dof. Later versions have tips that articulate in a single plane (Micro-Wrist; Computer Motion), providing six dof.

At the operator's console, the surgeon manipulates form-fitted handles while viewing a flat monitor (Fig. 3). Optional 3-D viewing is available by using polarizing glasses. The ZEUS system also is equipped for telementoring (Socrates; Computer Motion). A mentoring surgeon in another location

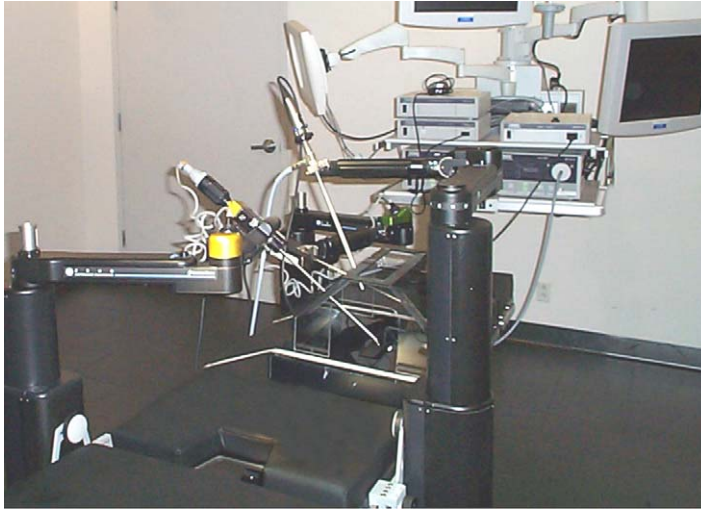


Fig. 2. The ZEUS master-slave device. Three robotic arms are mounted onto the operating room table and controlled from the console. (Courtesy of Computer Motion, Goleta, CA; with permission.)

has the same screen view as the operating surgeon. The two surgeons can communicate by voice and the mentoring surgeon can draw directly on the screen image to guide the operating surgeon.

The da Vinci system was designed using technology developed at the Stanford Research Institute. Similar to the ZEUS, the da Vinci system has three to four robotic arms, but the arms are mounted on a surgical cart that is positioned next to the operating table (Fig. 4). The tips of the instruments articulate in multiple planes (Endowrist; Intuitive Surgical) similar to the human wrist, providing the robotic arm with seven dof. At the surgical console, the surgeon views the operation through binoculars in true 3D (Fig. 5). The stereo images are captured by two parallel cameras with 0- or 30-degree lenses. At the console, the images are projected to create the impression that the surgeon's hands are holding the instruments over an open surgical field (Fig. 6). When a foot pedal is pressed, the surgeon's hand movements control the robotic arm holding the camera.

These master-slave devices offer great promise and their role in the operating room is being defined. No definitive studies demonstrate an advantage for robot-assisted surgery for a procedure already performed by conventional laparoscopy. In general surgery, for example, prospective randomized studies have compared robot-assisted and conventional laparoscopic surgery for Nissen funduplications [11] and cholecystectomies [10].

The robotic surgeries did not offer significant advantages and were associated with higher cost and longer operative times. Robot-assisted surgery may shorten the learning curve for surgeons with minimal laparoscopic experience, however [33,34].



Fig. 3. The ZEUS master-slave console. The surgeon views the operative field on a flat screen. The robotic arms are controlled using form-fitted handles at the end of the armrest. (Courtesy of Computer Motion, Goleta, CA; with permission.)



Fig. 4. The da Vinci surgical cart. The surgical cart is positioned adjacent to the operating room table. (Courtesy of Intuitive Surgical, Sunnyvale, CA; with permission.)

In addition, robotic surgery should be evaluated in the context of continuing improvements in technology and surgical technique. Force-feedback devices, better video imaging, and improved instrumentation will continue to make robot-assist surgery more effective.

### Clinical experience

In urology, the FDA has approved the da Vinci system for performing radical retropubic prostatectomies (RRP) and several series have been published [35–38]. Pasticier and colleagues [37]



Fig. 5. The da Vinci master-slave console. At the console, the surgeon views the operation through binoculars in true 3D. (Courtesy of Intuitive Surgical, Sunnyvale, CA; with permission.)

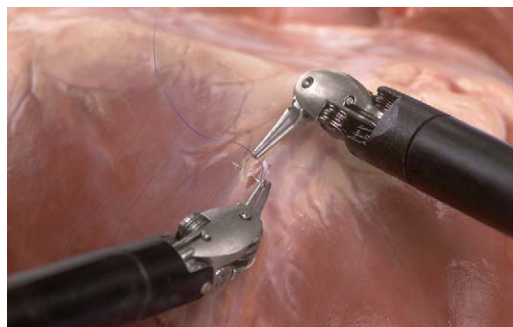


Fig. 6. The da Vinci master-slave controls. At the console, the images are projected to create the illusion that the surgeon's hands are holding the instruments over an open surgical field. The robot arms have seven dof. (Courtesy of Intuitive Surgical, Sunnyvale, CA; with permission.)

reported one of the earliest series using the da Vinci system to perform RRP on five patients. The mean operative time was 222 minutes. They noted that all steps performed by laparoscopic RRP could be performed using the da Vinci system and that the da Vinci system facilitated the creation of vesicourethral anastomosis. Another early series was reported by Rassweiler and colleagues [38]. They used the da Vinci system to perform RRP on six patients. The mean operative time was 315 minutes. They stated that the learning curve was steep, but less steep than conventional laparoscopic RRP.

Larger series with longer follow-up times have been published more recently. Bentas and colleagues [35] reported that over 100 da Vinci RRP with bilateral pelvic lymphadenectomy have been performed at the University of Frankfurt in Germany. They reported on their first 40 patients with 1 year of follow-up. The mean operative time was 498 minutes. The surgical time decreased by 22 minutes on average with each case. The average intraoperative blood loss was 558 mL and the transfusion rate was 32.5%. One case was converted to a standard laparoscopic RRP and one case was converted to an open RRP. The positive margin rate was 8% in patients who had pT2 tumors and 67% in patients who had pT3 tumors. Complications included two pulmonary embolisms, one deep vein thrombosis, one obturator nerve injury and one trocar injury to the epigastric artery. One year following surgery, 68% of the patients were completely continent and 16% used one pad per day for safety. Potency data was not reported.

The largest series for RRP performed using the da Vinci system is reported by Menon and colleagues [36] from Henry Ford Hospital in Detroit, Michigan. They have performed over 350 da Vinci RRP and have reported on 200 patients with complete data from their first 250 patients. The mean operative time was 160 minutes and the average intraoperative blood loss was 153 mL. Complications included three port hernias, three prolonged ileuses, one delayed bleed, and one deep vein thrombosis. The positive margin rate was 6%. The mean hospitalization was 1.2 days and the mean catheterization time was 7 days. At 6 months, 96% of patients were completely dry or using a pad only for security. Using a validated survey (expanded prostate inventory composite), 82% of men less than 60 years of age and 75% of men over 60 years of age had return of sexual function.

These early experiences with robotic RRP are encouraging, but large experiences from other institutions are needed. Longer follow-up that

documents the oncologic efficacy of robotic RRP also is needed. It has been suggested that robotic RRP simplifies laparoscopic tasks for surgeons with minimal laparoscopic experience. It is unclear, however, whether robotic RRP accomplishes this goal. The advantages and disadvantages of robotic RRP compared with open or conventional laparoscopic RRP need to be documented better, especially with regard to the learning curve involved.

Master-slave robotic devices have been used for various other urologic procedures. Guillonnet and colleagues [39] described the first telerobotic nephrectomy in humans using the ZEUS system. The nephrectomy was performed for a nonfunctioning right kidney. A larger series of robot-assisted, simple or radical nephrectomies has not been reported. Donor nephrectomies using the da Vinci system have been described [40]. Robot-assisted adrenalectomies [41,42] and pyeloplasties [43–45] have been performed. Menon and colleagues [46] reported performing da Vinci-assisted radical cystectomies in 14 men and three women. Ileal conduits and orthotopic neobladders were constructed by exteriorizing bowel through a small laparotomy incision. The mean operative times for the radical cystectomies, ileal conduits, and orthotopic neobladders were 140, 120, and 168 minutes, respectively.

### Telesurgery

Telesurgery refers to active control of the surgical instruments by a surgeon located at a remote distance from the operative theater with data transmitted over a telecommunications line. Although the surgeon's console and robotic arms of a master-slave device usually are located in the same room during surgery, the procedure can be performed with the surgical console located in another room, or even another state. Telesurgery has the potential to provide access to surgical expertise anywhere in the world [47,48], or aid in providing surgical care in hazardous locations such as battlefields and disaster sites.

The first international telesurgery was performed in 2001 by surgeons in New York on a patient in France [47,48]. The ZEUS system was used to perform a cholecystectomy. The surgery was completed successfully without complications, but several factors limit widespread implementation of telesurgery. First, transmission of data over telecommunications lines requires a large bandwidth. Furthermore, transmission over long distances results in signal latency; there is a delay

between the time the surgeon moves his or her instrument and when the movement is seen on the video image of the surgical field. Ideally, the signal delay should be less than 10 milliseconds to prevent overshooting of movements. Surgeons can compensate for delays of 200 to 300 milliseconds, but longer delays may make surgery difficult to perform [49]. Finally, data communications need to be 100% reliable and secure to prevent unauthorized viewing.

Telementoring, real-time teaching by a mentor who is not present at the site of the operation, is feasible. In 1994, Kavoussi and colleagues [50] demonstrated that the operating surgeon could be guided by a remote surgeon in a separate room. The remote surgeon can use the AESOP robotic arm to manipulate the camera. Others have demonstrated that telementoring can be performed successfully between the United States and centers in Austria [51–53], Italy [53,54], Singapore [53,55], and Thailand [51].

### Robotic surgical training

A significant drawback to robot-assisted surgery is the learning curve. It has been proposed, however, that robotic surgery shortens the learning curve for laparoscopic procedures for practitioners with no previous laparoscopic training. Robotic surgery restores 3-D visualization and wristlike flexibility, allowing surgeons experienced in open procedures to operate in a more intuitive environment. This assertion is supported by a report by Yohannes and colleagues [34]. They compared the learning curves for eight physicians in performing a dexterity task and free-hand suturing in a dry laboratory using robot-assisted or conventional laparoscopy. The participating physicians were classified as novice or experienced laparoscopists. For novice laparoscopists, the learning curves for robot-assisted tasks were significantly shorter when compared with conventional laparoscopy. For experienced laparoscopists, however, robotic surgery did not seem to offer any advantages.

A report by Menon and colleagues [33] describes a structured program for learning to perform robotic RRP. Menon had no previous laparoscopy experience, and he was mentored to perform robotic RRP by Vallancien and Guillonnet, who had a combined laparoscopic RRP experience of over 600 cases. They compared the results of 40 robotic RRP performed by Menon with 40 laparoscopic RRP performed by either

Vallancien or Guillonnet. The mean operative times for the robotic and laparoscopic RRP were 274 minutes and 258 minutes, respectively. The operative time for robotic RRP decreased with experience. After 18 cases the operative time for robotic RRP had decreased to that of laparoscopic RRP. The estimated blood loss, change in hemoglobin, positive margin rates, and overall complication rates were similar between the two groups.

Master-slave robots have been promoted as a tool for simplifying laparoscopic tasks that require a high level of dexterity. The cost of master-slave robots is prohibitive at many centers, whereas conventional laparoscopy is widely available. Furthermore, the increased dexterity of robotic surgery is not necessary for most extirpative urologic procedures. Therefore, it can be argued that conventional laparoscopy serves as a bridge to robotic surgery. Many of the skills required for conventional laparoscopy are translated readily to robotic surgery. Laparoscopy provides experience with tissue handling, recognizing anatomic structures through a laparoscope, and operating without tactile feedback. Furthermore, laparoscopic skills may be necessary to complete the surgery without an open conversion in the event of a mechanical failure.

### Future direction

Robotic surgery is near the verge of entering the mainstream of clinical practice. Advances in technology will continue to make robotic surgery attractive. The greatest impediment to widespread application is cost. As the medical robotic industry grows, the cost of the devices and their reusable components will decrease. Continuing efforts to develop a force-feedback mechanism will allow surgeons to appreciate the strength and texture of tissues. Smaller and more mobile versions of the robotic devices will be more user-friendly for the surgeon and the operating room staff.

Another exciting prospect is the merger of robotics and virtual-reality simulation. Virtual-reality trainers will allow surgeons to train and practice robotic surgery in a virtual 3-D environment [56–58]. Surgeries of various difficulty can be simulated under a variety of conditions. Difficult tissue dissection, complex surgical anatomy, and heavy bleeding can be simulated for training purposes. The entire procedure and surgeon's movements can be recorded and later reviewed by a mentor. This may represent a cost-effective

and safe method for training and credentialing surgeons.

Virtual-reality technology also may allow physicians to download patient imaging studies such as MRIs and CTs into a computer system to create a patient-specific training environment. Physicians can practice an operation in an environment that incorporates patient-specific anatomy and pathology. The possibilities and potentials for this technology are limited only by one's imagination. For example, these 3-D images can be superimposed on the surgical field during the operation to reveal structures deep to the visualized surface. A mentoring surgeon's movements during a training session may be used to control an off-line robot, guide the operating surgeon, or prevent the surgeon from making an error in surgical technique.

## Summary

In 1965 Gordon Moore, cofounder of Intel Corporation, made his famous observation now known as Moore's law. He predicted that computing capacity will double every 18 to 24 months. Since then, Moore's law has held true; the number of transistors per integrated computer circuit has doubled every couple of years. This relentless advance in computer technology ensures future advances in robotic technology. The ultimate goal of robotics is to allow surgeons to perform difficult procedures with a level of precision and improved clinical outcomes not possible by conventional methods. Robotics has the potential to enable surgeons with various levels of surgical skill to achieve a uniform outcome. As long as urologists continue to embrace technological advances and incorporate beneficial technology into their practice, the outlook for patients remains bright.

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## Overview and fundamentals of urologic robot-integrated systems

Mohamad Allaf, MD, Alexandru Patriciu, MS, Dumitru Mazilu, PhD,  
Louis Kavoussi, MD, Dan Stoianovici, PhD\*

*Brady Urological Institute, D0300, Bayview Medical Center,  
Johns Hopkins University, 5200 Eastern Avenue, Baltimore, MD 21224-2736, USA*

Advances in technology have revolutionized urology. Minimally invasive tools now form the core of the urologist's armamentarium. Laparoscopic surgery has become the favored approach for treating myriad complicated urologic ailments. Minimally invasive surgery could not exist without an active man-machine partnership, which allows urologists to order CT scans, use laser or ultrasonic energy, and conduct common procedures such as ureteroscopy. Surgical robots have

started to populate the operating rooms of large medical centers. These robots represent the next evolutionary step in this fruitful partnership.

Current minimally invasive methods, despite their advantages, have inherent limitations. For example, although laparoscopy improves convalescence, decreases postoperative pain, and avoids large, unsightly scars, it is not yet a universally accepted and mastered skill among urologists. Limitations such as a steep learning curve, two-dimensional visualization, and decreased tactile feedback, dexterity, and maneuverability make some laparoscopic tasks such as intracorporeal suturing more difficult to perform than in open surgery.

The introduction of robotic technology in urology not only circumvents some of these limitations, but also affects how urologists learn, teach, plan, and operate. Several robots are commercially available with functions ranging from manipulating the laparoscope to facilitating the performance of transcontinental telesurgical laparoscopic and percutaneous procedures. As technology evolves, robots not only will improve performance in minimally invasive procedures, but also enhance other procedures or enable new kinds of operations.

### History

Originally derived from the Czech word *robota*, which means labor, the term *robot* now is used widely [1]. The industrial revolution documented the capability of automated tools to facilitate and improve manufacturing. As the need for production versatility emerged, the area of

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\* Corresponding author.

E-mail address: [dss@jhu.edu](mailto:dss@jhu.edu) (D. Stoianovici).

factory robotics was born and grew rapidly during the 1970s and 1980s. The potential applications for such robots within medicine were realized soon thereafter, and robots were introduced into the health care system to aid in four main categories: supportive roles, laboratory assistance, rehabilitation, and surgery [2]. Systems such as Help-Mate (Pyxis Corporation, San Diego, California) were developed to fulfill supportive and laboratory assistant roles [3,4]. This commercially available robot acts as a courier within hospitals delivering food, radiographs, and medications.

Rehabilitative efforts preceded the development of surgical systems and focused on developing tools to aid physically disabled patients, specifically in the areas of locomotion, movement of artificial limbs, and gaining independence in tasks of daily living. Such efforts produced robotic systems that have improved significantly the quality of life of these patients [5,6].

Not until the mid-1980s were robots introduced into the operating room, first in the fields of neurosurgery and orthopedic surgery, where the anatomy provides fixed constant landmarks [7]. These first machines were predefined-task robots designed to aid in operations requiring high levels of accuracy and precision, such as stereotactic neurosurgical procedures (Minerva, NeuroMate, Integrated Surgical Systems, Davis, California) and hip replacement surgeries where the robot mills a cavity to fit the implant exactly (Robodoc, Integrated Surgical Systems) [8–10]. Robotics in urology was slower to develop, largely because of the challenges imposed by deformability and high mobility of urologic organs. The difficulty of reaching soft tissue targets called for more sophisticated systems. As technology improved, innovative research produced several robotic systems either applicable to or purposely designed for urology.

Probot was introduced in 1989 by the pioneering scientists at Imperial College in London and deserves mention as perhaps the first robot used in urology [11,12]. This device was built to aid in transurethral resection of the prostate (TURP). The relatively fixed position of the prostate and the repetitive motions involved in TURP made this an attractive early candidate for robotic assistance. The system used video and ultrasound information and the surgeon predefined the desired resection area on the ultrasound images. The robot then proceeded to resect as instructed. Finally, hemostasis was achieved using manual electrocautery.

Probot first was used clinically in the spring of 1991, representing the first use of a robot to excise significant tissue in a human patient. The system had major drawbacks, however, such as the inaccuracy of transrectal ultrasound (TRUS) in determining prostate dimensions, and never achieved widespread use.

Robotic systems involved in urology can be grouped in two main categories according to their operation mode. The first category comprises complex, computer-integrated, surgical systems for which the operator defines the task and the system accomplishes the task on its own. The Probot falls into this category. After the surgeon defined the resection area, the robot performed the resection without further surgeon intervention. The second category includes surgical assistants, which are operator-driven systems, and exhibits low integration with the medical environment. In such a system the surgeon continuously controls the position of the robot and decides what task needs to be performed.

### Computer-integrated surgical systems

Computer-integrated surgical systems are a new class of “intelligent” surgical tools that may include surgical robots. Although these systems are not yet a reality, they represent a vision for the operating room of the future and define the architecture of interaction between its components. At their core, these systems include several steps: (1) preoperative planning, usually based on medical images and a unified database of patient information, (2) intraoperative registration (matching the patient to the preoperative images), (3) treatment delivery that may use a combination of robotically assisted and manually controlled tools for carrying out the plan, and (4) postoperative analysis, which includes systems for facilitating patient follow-up and quality control (Fig. 1).

Robotic manipulators represent a key subsystem within the architecture of computer-integrated surgical systems. The main advantages of robotic surgical tools are (1) accurate registration to preoperative imaging studies, (2) consistent movement free of fatigue and tremor, (3) the ability to work in imaging environments unfriendly to human surgeons, and (4) the ability to reposition instruments quickly and accurately through complex trajectories or onto multiple targets. With robotic systems, the task either may be predefined by the surgeon based on

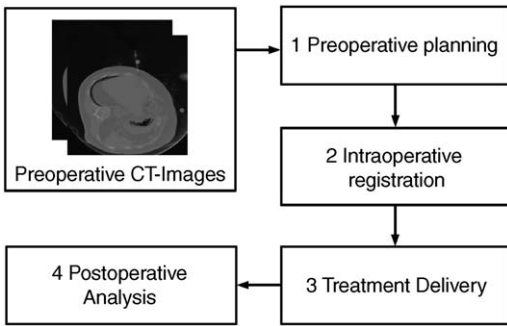


Fig. 1. Computer-assisted interventions workflow.

preoperative or interventional data, or for more dynamic procedures, defined by the surgeon as the operation progresses.

Thus, computer-integrated surgical systems usually are image-driven and excel at precisely reaching a target specified by the surgeon. In interventions relying on radiographic imaging, such as percutaneous needle cases, these systems are used to guide and sometimes insert a needle, instrument, or probe into a desired target. Their purpose is to act as a trajectory-enforcement device, correctly aligning the needle based on images from ultrasound, C-Arm, or biplanar fluoroscopy units, or CT or MRI scans. Image-guided systems take advantage of the capability to compute accurately a transformation (register) from the medical image space to the robot space. The robot then can manipulate precisely instruments to reach the corresponding coordinates in the patient space that are selected on the medical image. These systems integrate preoperative planning and intraoperative decision-making, and subsequently actualize the intent of the surgeon, minimizing error.

For surgeon-driven robots, however, the surgeon directly controls the motion of the instruments held by the robot. These systems combine the dexterity of robotic systems with the surgeon's perception and judgment performing scaled-down, steady, tremor-free motion. By increasing resolution of movement and vision, these robots make laparoscopic tools more dexterous. Robots can emulate the movement of the human hand and wrist much better than traditional laparoscopic instruments. Additionally, they can be added transparently within the framework of larger integrated systems, fusing preoperative data such as imaging with real-time information and providing additional insight on the task. The

complexity of these systems varies from simple laparoscopic assistants that hold and orient a laparoscope to complex surgical telemanipulators.

### Overview of robotic surgical systems

Three essential and general components of robotic systems are the manipulator, image-acquisition device, and computer. A discussion of these components is crucial to understanding medical robotic systems.

Surgical manipulators are electromechanical arms equipped with sensors and actuators responsible for holding and precisely moving instruments under computer control. The most common kinematic architecture of surgical manipulators uses the remote center of motion (RCM) concept [13,14]. The RCM mechanism was developed in 1995 by a research group at IBM and is a feature specific to surgical robots (as opposed to industrial robots). The RCM mechanism is used by the surgical manipulator to enable and facilitate the pivoting of instruments about a fixed point in space. This mechanism enables minimally invasive instruments to preserve a consistent entry point (or port) throughout the procedure. The RCM concept aims to reproduce the surgeon's natural motion during laparoscopy. For example, following insertion of a laparoscopic instrument through a trocar, RCM allows it to pivot about a fixed point in space: the point where it enters the body. Almost all contemporary surgical systems use variations of the RCM concept.

The image-acquisition device is another critical component of robot-assisted surgical systems and may be based on various imaging modalities (eg, conventional video, infrared, ultrasound, radiograph, or MRI). For example, a predefined-task robot built to aid in achieving percutaneous access may use fluoroscopy or CT data in planning and deciding where to advance the needle, whereas a surgeon-directed robot manipulating laparoscopic instruments depends on video for its function. Because laparoscopy depends highly on the quality of the image, there has been considerable progress in optimizing laparoscopic imaging. Stereo endoscopes allow for three-dimensional visualization of the surgical field [15], which increases surgical performance by enabling more precise dissection between delicate anatomic planes and providing razor-sharp precision when handling sutures and minute tissue layers [16,17]. High-definition (HD) imaging is now available,

although not in widespread use. HD camera chips produce more than 2 million pixels of resolution (approximately four times better than the best traditional camera chips). It is estimated that the current cost of a complete HD video system for the operating room ranges from \$250,000 to \$500,000, making it prohibitive for most medical centers [15]. As the technology matures and costs drop, however, HD technology may become more available in the operating room.

Image-acquisition systems can introduce compatibility issues, especially when using MRI. Although MRI yields excellent soft-tissue images, its high magnetic fields may generate forces that are 27 times the weight of the part. This occurs on ferromagnetic objects such as traditional metal robots. MRI also can produce substantial thermal damage and other undesirable effects. There is strong reason, however, to build an MRI-compatible robot because of the superior imaging capabilities of this technology, especially in urology, where MRI may be the ideal modality to target prostatic lesions precisely. Although there is much current research toward building MRI-compatible robots, no clinically applicable systems of this type are commercially available [18–22]. The authors' URobotics group has developed an MRI-compatible positioning arm [23,24] and a precision hydraulic motor compatible with this environment [21]. A multi-imager-compatible robot for needle access of the prostate is under development; its main application will be for MRI-guided brachytherapy.

The computer is the third essential component of surgical robotic systems. In addition to recording data regarding the procedure at hand, computers provide a link between the "data world" of medical information (images, sensors, and databases) and the physical world of surgical actions. They integrate preoperative data with real-time information and relay this to the surgeon in a meaningful manner. This information then can be used to improve surgical planning, intraoperative decision-making, and real-time control of surgical instruments.

With computer-integrated surgical systems, the surgeon selects an anatomic target on a preoperative imaging study and the robot automatically and precisely delivers the desired tool or treatment at that anatomic location in real time and space. Within urology, the development of image-guided robotic systems has focused on three areas: TURP, prostate biopsy, and percutaneous renal access. As discussed previously, the Probot system was developed to aid with TURP procedures.

### *Prostate biopsy*

Robotic systems targeting the prostate aim to exploit its relatively fixed position within the pelvis. An Italian group has developed a system for conducting transperineal prostate biopsies [25,26]. Four video cameras record the position and configuration of the patient's body and integrate that data with TRUS imaging of the prostate to allow accurate positioning of the needle. The surgeon selects biopsy targets on TRUS images and the robot obtains them. Despite its documented accuracy (within 1–2 mm in animal studies), cost and set-up time have hindered this system's clinical feasibility.

### *Percutaneous renal access*

Obtaining percutaneous renal access is a complicated task that requires great skill and experience, especially in cases where the collecting system is not dilated. Inaccurate needle placement and manipulation risk injuries to adjacent structures and can be difficult. Some urologists have relinquished this task to interventional radiologists who use fluoroscopic, CT, or ultrasound guidance. Thus, there is a great need for a system to automate and facilitate this process.

In 1994, a group at the Imperial College in London investigated a robotic system to assist the urologist with intraoperative percutaneous renal access [27]. They used a passive, encoded, five-degree-of-freedom (DOF) manipulator equipped with electromagnetic brakes mounted onto the operating table. The access needle was positioned manually as prescribed by a computer that triangulated the calyx location from multiple C-arm images [28]. In vitro experiments evaluating system performance demonstrated a targeting accuracy of less than 1.5 mm. Nevertheless, no human trials have been performed with this system.

A similar system was developed at the Johns Hopkins University that differed from the Imperial College system in that it used an active robot (LARS) and biplanar fluoroscopy [29]. In this system, the surgeon selects the target calyx on two images and the robot proceeds to insert the needle into the desired location. Although accuracy studies documented a margin of error of less than 1 mm, in live porcine percutaneous renal access experimentation the success rate at first attempt was only 50% [30]. Problems contributing to this included the mobility and deformability of the kidney, problems with needle deflection, and rib interference. This system, however, proved the

feasibility of performing fully automated needle placement in soft tissues. In addition, it represented another step in the evolution toward that goal in clinical practice.

The authors' URobotics group has developed a system for image-guided percutaneous access [31]. Unlike its predecessors, which relied on computer-based imaging and targeting, this system was designed to mimic standard percutaneous renal access technique, providing an easy-to-use, surgeon-friendly device. The system is based on an active and radiolucent needle driver, percutaneous access to the kidney (PAKY) [32]. PAKY uses an axial-loaded rotational-to-translational friction transmission principle to grasp, stabilize, and advance an 18-gauge access needle into the kidney percutaneously. The needle is secured by the needle driver along its barrel near the tip to minimize deflection or bowing of the unsupported length of the needle during passage through various tissue planes [33]. Another generation automated the needle orientation procedure by adding an RCM module [34]. The RCM module orients PAKY and allows the needle tip to pivot about a fixed point on the skin. This allows the urologist to align the needle properly at the skin level along a selected trajectory path during fluoroscopic imaging by remote control, thus minimizing radiation exposure to his or her hands. The most recent system, AcuBot [35], augments a Cartesian positioning stage and an integrated passive arm for initial positioning, as presented in Fig. 2.

These systems, in their evolving stages, have proven feasibility, safety, accuracy, and efficacy in

limited clinical trials. A more extensive trial by Su and colleagues [36] validated these results. In this trial, 23 patients undergoing access by the robot were compared with a contemporaneous cohort of patients undergoing access by standard techniques. The robotic system was successful in gaining access 87% of the time with the number of attempts and time to access comparable to those of the standard technique. Furthermore, the system has been used to obtain biopsy specimens and ablate targets in kidneys and spine successfully and to gain percutaneous renal access in international telesurgical cases [37,38]. Although its use in humans has been limited, this system demonstrates great promise and is likely to provide the mechanical platform for a completely automated system for percutaneous renal access.

### Surgeon-driven systems

In contrast to robotic integrated systems that take a prescription of instructions based on imaging information and conduct the task at hand, surgeon-driven systems continuously receive input from the surgeon and in real time translate that into action. Thus, every movement is dictated by human perception and judgment. Such systems can eliminate tremor, scale motion, and aid in manipulation of tissue in confined spaces, and have the potential to provide haptic (tactile and force) feedback. Surgeon-driven systems can be divided into surgical assistants such as endoscope manipulators and surgical master-slave



Fig. 2. AcuBot, a robot for image-guided needle procedures.

manipulators, systems that enhance a surgeon's instrument manipulation. Some of these robots are commercially available and used daily.

### *Endoscope manipulators*

Surgeons conducting laparoscopic procedures typically relinquish full control over their operating field of vision because the job of controlling the laparoscope is delegated to another individual. In addition to imposing financial and logistic burdens, the need for an additional assistant creates the potential for miscommunication and inaccurate movements as a result of fatigue or tremor. This can be frustrating and potentially dangerous. Mechanical devices to hold the laparoscope were built to circumvent this problem. These first-generation systems required manual adjustment and were cumbersome [39,40].

Computer-controlled robots have been developed to address these problems. The first surgeon-driven robot to gain US Food and Drug Administration Approval (FDA) approval is one such system: the Automated Endoscopic System for Optimal Positioning (AESOP; Computer Motion, Goleta, California). AESOP has six DOF, two of which are passive, and is a particular implementation of the RCM concept. AESOP is composed of a planar two-DOF manipulator attached to a vertical translation stage. The translation stage is attached to the operating table and the robot end-effector accommodates the laparoscopic endoscope through a passive two DOF joint. A final rotation allows for camera orientation. When the endoscope is passed through the entry port, its motion is restricted to three rotations about the entry point and one translation along the endoscope axis. The system is mounted easily on the operating room table and can be stored conveniently by mounting it on a special cart. AESOP was developed to provide the surgeon with direct and precise control over the visual field while both arms remain free for the delicate maneuvers required in surgical procedures. AESOP can hold and control a laparoscopic camera through a hand-, foot-, or voice-control interface.

AESOP is used routinely at several institutions and in various surgical fields, including urology [41–43]. Its success and popularity among surgeons attests to its ease of use, reliability, safety, and affordability. Furthermore, this system's usefulness has been confirmed by various studies. In terms of its learning curve, studies have shown

that one can learn to control a laparoscope with AESOP in the same amount of time to learn manual control [44]. Kavoussi and colleagues [45] evaluated the quality of the image produced by AESOP versus a human assistant. This blinded study concluded that the AESOP-controlled cases had steadier images and less instrument collisions. Partin and colleagues [46] reported on a series of 17 laparoscopic cases conducted by a solo surgeon. At least one AESOP was used to control the camera and an additional AESOP was used as a retractor. Operating room time and cost were equivalent when compared with similar human-assisted procedures. Furthermore, AESOP also has had a significant role in the realization of telesurgery in urology [47].

### *Master-slave systems*

The master-slave concept involves a “master” unit that the surgeon controls. The surgeon's commands (usually movements) are processed by a computer and sent to “slave” components that carry out the task at hand in real time. These types of systems first were introduced in the 1990s [48,49]. Using master-slave robots, a surgeon seated at a console manipulates levers that control mechanical instruments inside a patient's body. These systems represent a paradigm shift in surgery because the physician is no longer manipulating surgical instruments directly. Although physical connections initially required the surgeon's console to be in the same operating room as the patient, these systems have great potential for remote telesurgery. Furthermore, because the surgeon's motions can be processed by the computer, the real-time movements generated can be enhanced greatly.

Through information processing, master-slave robotic systems can filter out physiologic tremor and allow finer movement by motion scaling. Motion scaling is the concept that a movement by the surgeon at the master unit can be amplified or dampened at the end-effector slave unit. Conversely, master-slave systems theoretically can process information from the slave unit to provide useful feedback to the surgeon. Tactile and force feedback can be especially helpful and are referred to collectively as *haptic feedback*. Haptics is an active area of research within the engineering community [50,51]. Much research exists investigating new kinds of tactile sensors [52–56]. Although promising, numerous theoretical questions regarding the best way to convey haptic

information remain unanswered. In addition, there are several technical obstacles to overcome vis-à-vis hardware development, signal processing, and systems integration before true general haptic feedback will be possible [2,34,55,56]. An additional advantage to these master-slave systems is the potential to adjust the surgeon's view constantly to correspond automatically with instrument movement, which can eliminate the sometimes counterintuitive movements of conventional laparoscopy.

Bowersox and colleagues [48] evaluated an early master-slave prototype designed for use in conventional open operations. This system was equipped with two robotic arms and included a haptic interface providing force feedback. The surgeon had a three-dimensional view of the surgical field and from a nonsterile console was able to complete in vivo porcine procedures successfully, including nephrectomy and ureteroureterostomy.

Zeus (Computer Motion) and da Vinci (Intuitive Surgical, Mountain View, California) represent the most recent generation of master-slave systems. These robots are in clinical use in large medical centers and have generated much excitement.

The da Vinci system consists of a surgeon's console, a control unit, and a three-arm surgical manipulator. Two of the arms are used for manipulating surgical instruments, and the third arm controls the laparoscope. The instruments have seven DOF, including rotation aimed at reproducing the human wrist. The surgeon sits at the console and is presented with a high-resolution three-dimensional view of the surgical field. The system uses the principle of motion scaling and applies a motion filter to eliminate physiologic tremor.

First used in Europe for cardiac surgery, the da Vinci system received FDA approval in July 2000 and has been used to perform various urologic operations. Its first and most extensive application in urology has been in robot-assisted laparoscopic prostatectomy (LRP). Schuessler and colleagues [57] reported the initial case of LRP in 1997. Guillonnet and Vallancien [58] refined this minimally invasive approach to radical prostatectomy and popularized the technique.

LRP, however, has proved a challenging operation. To facilitate this procedure and flatten the associated learning curve, several groups have developed robot-assisted LRP programs [59–62]. Menon and colleagues [63] recently reported

results of their initial 200 cases and concluded that robotic LRP was comparable to conventional LRP and open radical prostatectomy in terms of oncologic control and complications. Furthermore, because they were not skilled laparoscopic surgeons but had extensive experience with open radical prostatectomy, they found the robotic procedure much easier than conventional LRP. Although these results are encouraging, they represent the initial experience and require validation. Other investigators have published reports and limited case series of other urologic procedures using the da Vinci system, including donor nephrectomy, pyeloplasty, and adrenalectomy [64–66]. These early reports are encouraging and seem especially relevant to open surgeons who want to offer a minimally invasive alternative without struggling with the steep learning curve associated with conventional laparoscopy.

A similar master-slave system, the Zeus robot, received FDA approval in September 2002 and represents an alternative to da Vinci. It uses an AESOP unit to control the laparoscope and has two additional arms to manipulate the surgical instruments. Originally, the Zeus end-effectors exhibited limited dexterity and possessed fewer degrees of freedom than da Vinci, but this problem was circumvented with the introduction of the MicroWrist line of end-effector tools [67]. Zeus has been used successfully in several pilot studies. One study compared da Vinci and an earlier version of Zeus during porcine operations and concluded that both systems are effective for the operations performed, but da Vinci was associated with lower operative times and a flatter learning curve [68]. The Zeus system used in this study was an earlier version predating the MicroWrist technology and thus was handicapped by its instruments' lack of articulating tips. Additionally, no set-up data were compared in this report.

Although Zeus and da Vinci have made robotic surgery a reality, they have failed to reproduce tactile sensation completely. The haptic feedback built into these systems is limited by current technology that fails to provide meaningful feedback. Furthermore, the cost of these systems remains prohibitive for most medical centers. For example, it is estimated that the da Vinci system costs approximately \$1 million with a maintenance fee of \$100,000 per year [69]. As robotic technology evolves, these systems will become more useful and their costs will drop. The next few years promise to be exciting.

Computer technology and robotic systems have proved useful in medical training and remote medical assistance. There is a growing disparity between the public's expectation for highly technical health care (such as minimally invasive surgery) and the number of experienced and qualified surgeons available to provide it [70]. One innovative way to bridge this gap is telemedicine. This concept allows specialists in remote locations to collaborate with less-experienced local surgeons in several ways. They can be present (telepresence), offer advice and training (telementoring), or participate directly in operations by way of robotic manipulators (telesurgery). Such systems recently have been implemented successfully.

Another emerging and important area within medical robotics involves systems specifically designed to train surgeons. Robotic and computer simulations can enable surgical training to be performed in virtual reality or simulated environments without risk to humans or animals. Furthermore, such devices may be able to record the training process, measuring and tracking it over time, which will allow constant refinement in the way future physicians are trained.

### Telementoring and telesurgery

The real-time data exchange of medical information between physicians in different locations is known as *telemedicine*. *Telementoring* describes the assistance of an experienced surgeon in a remote operation, whereas *telesurgery* implies the remote surgeon's active involvement in the operation, typically through remote control of surgical instruments. The increasing accessibility of telecommunications systems, from telephone lines to high-bandwidth fiber-optic and satellite transmissions, has facilitated the communication between physicians separated by large distances [71]. Teleconferences and the exchange of medical images and data have become common, especially with the advent of the Internet. Teleconferences and teleconsultation in surgery have been shown to be of benefit in various studies.

Kavoussi and colleagues published initial reports of telementoring and telesurgery in 1994 [47,72]. These reports were followed by reports of various intercontinental operations [73]. In most cases, the remote surgeon's role was limited to the operation of a robot manipulating the laparoscope, and in some cases a telestrator system to highlight structures on the video stream. Time

delay can be a major challenge during such operations. Lag times for transmission of data during these procedures, however, have been reported to be less than 200 milliseconds, which is hardly noticeable [74].

The first transatlantic telerobotic operation using two robots was performed successfully between Baltimore, Maryland, and Munich, Germany, in April 2001 [75]. The remote surgeon controlled the laparoscope using the AESOP system from his home and used the PAKY-RCM tandem robot as a laproscopic tissue retractor. In addition, the remote surgeon had access to a telestration machine and controlled the carbon dioxide insufflator and electrocautery device. This was accomplished through the use of four integrated services digital network lines, each transmitting at 128 kilobytes/s.

In September 2001, history was made when a 68-year-old female in Strasbourg, France underwent an uneventful laparoscopic cholecystectomy by a remote surgeon operating the Zeus robotic system from New York [76]. With the continued development of advanced robotic systems and the evolution of communication technology, expert medical care will be available to patients anywhere in the world.

One of the goals of telemedicine is to deliver health care in medically underserved areas and to increase medical access to those needing it most [77]. Additionally, telesurgery has potential applications in armed conflicts or prolonged space missions where qualified medical care may not be readily accessible. Before these goals become reality, however, several issues must be addressed.

Telemedicine of any kind depends on continuous and high-quality signal transmission [71]. Although local set-up theoretically does not require a surgeon, experienced surgeons must be on hand at the patient's location to intervene in case of system or transmission failure. Additionally, because of the necessary technical assistance in both locations, coordination of such efforts, especially across several time zones, has proved challenging. Another serious obstacle is that medical technology is advancing too rapidly for legislation to keep pace. Among the issues to be addressed are interstate and international licensure regulations, billing, informed consent, and malpractice. As telemedicine becomes a reality, it will become necessary to set international standards, rules, regulations, and safety measurements to protect patients. The advanced technical requirements and high costs of telesurgery are

satisfied only by a few specialized centers worldwide. The field is expected to expand, however, as robotic systems become more widespread and as reliable, low-cost, communication systems become more readily available.

The first commercially available telementoring system is Socrates (Computer Motion). The system allows for online collaboration between the surgeons through video-conferencing and shared control of the endoscope and other devices connected to a common control center. Because the system implements all the standard telementoring facilities needed, it is well suited for classic and minimally invasive surgical training.

### Robotic training devices

Minimally invasive techniques require specialized skills that are difficult to learn. For residents, exposure in this area is increasing as these techniques become more popular. Nevertheless, a training fellowship is necessary for most physicians and significantly flattens the learning curve [78]. Additionally, fully trained surgeons attend training courses and observe specialists in hopes of learning the necessary skills. Although direct experiences with experts are crucial, in laparoscopy, for example, a constant surgical volume is necessary to maintain and expand acquired skills [79]. Devices to help preserve and hone minimally invasive surgical skills thus are much needed. Despite the progress made in surgical robotics, animal surgery remains the mainstay of laparoscopic training.

Several training systems for minimally invasive surgery have been proposed and developed, but none are in popular use. Although virtual reality systems seem promising, other model-based tools also demonstrate great potential.

A system recently developed in the authors' URobotics Lab, LapMan [80], consists of a high-fidelity synthetic torso whose shape and contours are consistent with the male human anatomy based on data from the Visual Human Project of the National Library of Medicine (NLM) [31]. This model allows for the in situ inclusion of abdominal animal organs. Additionally, it presents a displaceable abdominal wall that can be pressurized and includes simulation of respiratory motion by connecting the system to a ventilator (Fig. 3).

The idea of virtual reality (VR) simulators for training purposes is appealing. Creating a three-dimensional, anatomically correct environment representing different scenarios has great potential. Unfortunately, the technology of VR simulators for surgery is in its infancy and remains rudimentary compared with that of other industries such as aviation. Nevertheless, VR simulators have been validated as a teaching tool for laparoscopy, and investigators continue to look for ways to improve this technology [81,82].

A unique VR system recently developed at George Washington University uses the NLM Visible Human dataset to generate surface-based geometric data of the lower urinary tract [83]. These geometric data then are associated with three-dimensional texture maps developed from actual endoscopic procedures to generate a real-time



Fig. 3. Synthetic torso during da Vinci laparoscopy training.

simulator of lower-tract endoscopy. This system allows its users an experience in virtual endoscopy complete with haptic feedback. The feasibility of such systems is encouraging for the future of training in urology.

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## Nuances in the optimum placement of ports in pelvic and upper urinary tract surgery using the da Vinci robot

Ashok K. Hemal, MD, MCh, FACS<sup>a,\*</sup>, D. Eun, MD<sup>a</sup>,  
Ashutosh Tewari, MD<sup>a</sup>, Mani Menon, MD, FACS<sup>a,b</sup>

<sup>a</sup>*Vattikuti Urology Institute, Henry Ford Hospital, 2799 West Grand Boulevard, K-9, Detroit, MI 48202-2689, USA*

<sup>b</sup>*Department of Urology, Case Western Reserve University, 11000 Euclid Avenue, Cleveland, OH 44106-4931, USA*

During the past decade, advances in laparoscopy have revolutionized urology. The recent success of robotic applications in urologic surgery has caused much fascination with this technology because of the prospect of laparoscopy becoming technically feasible for urologists not adept in laparoscopy for advanced urologic procedures. This interest has galvanized further the movement toward minimally invasive urologic surgery. Robotic technology is not universally available, however, and remains confined largely to large teaching institutions and centers of excellence. Access is limited mainly by prohibitive costs. Robotics offers promising potential to overcome the shortcomings of laparoscopy and redefine standards of care in urology.

Port placement is the key to success in robotic surgery. Poor patient positioning and inadequate placement of ports will lead to a cumbersome and frustrating experience during robot-assisted surgery. Therefore, early robotic experiences in the various types of urologic surgery (eg, upper- and lower-urinary tract, uro-gynecology, and infertility) typically have been fraught with difficulty because of uncertainty with respect to patient positioning and port placement. Individual variations of patient height, weight, body mass index, bony pelvis configuration, and muscular build can

affect the available length and mobility of the robotic arm. In the initial setup, these two factors are of paramount importance to a successful outcome.

This article shares the authors' experience in optimizing patient setup, port placement, and installation of the robot in various urologic procedures using the da Vinci robotic system. The authors give a general description on patient positioning, port placement, and installation of the robot with respect to the individual operations, followed by an explanation of important nuances, general principles, and caveats gained through experience.

### Material methods

In the authors' experience of over 1200 cases of robotic surgery, various procedures have been performed, including anatomic radical prostatectomy for localized cancer of the prostate, retro-pubic prostatectomy for benign hyperplasia of the prostate, radical cystectomy with urinary diversion for muscle-invasive cancer of the bladder in men and women, pyeloplasty, adrenalectomy, nephrectomy, radical nephrectomy, partial nephrectomy, hysterectomy, myomectomy, colposuspension, and vaso-vasal and vaso-epididymal anastomosis using the da Vinci Robotic System. The following description is based on the experience gained over 3 years and is intended as a guide for novice robotic surgeons in their initial experience.

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\* Corresponding author.

E-mail addresses: [akhemal@hotmail.com](mailto:akhemal@hotmail.com)  
[ahemall@hfhs.org](mailto:ahemall@hfhs.org) (A.K. Hemal).

### *Patient positioning and port placement*

Patient positioning and operating room setup should remain consistent and reproducible according to the specific operation. In contrast, the authors' experience has taught that optimal port placement requires individual patient considerations that result in subtle adjustments to the standard approach.

### *Pelvic operations*

*General principles in patient positioning.* After induction of general anesthesia, the patient's arms are tucked securely to the patient's side using an underlying bed sheet to avoid the risk for brachial plexus injury. The patient is padded generously, giving consideration to pressure points and areas of friction. After the patient's legs are placed into lithotomy using Yellowfin stirrups (Allen Medical Systems, Acton, Massachusetts), the caudad portion of the operating table is detached or lowered completely. Next, the patient's upper torso pressure points are padded and secured in anticipation of positioning the patient into a steep Trendelenburg position. This is done using two Ulnar Nerve Protector foam pads (EHOB, Indianapolis, Indiana) placed in crossing fashion across the patient's thorax and securely taped to the operating table (Fig. 1). This will prevent the patient from sliding cephalad once steep Trendelenburg is used.

At this point, the operating table height is brought down to its lowest possible position and Trendelenburg position is set to its maximum limit. The patient is prepped and draped from sternum to mid thigh and as lateral on the abdomen as possible. An 18F Foley catheter then is inserted on the sterile field and the anesthetist is requested to place an oro-gastric tube. Anesthesia places a Mayo stand at the head of the table hovering above the patient's head, which serves as protection for the patient's face when setting down the bulky laparoscope-camera combination or instruments, as well as a stable and well-used arm support for the patient-side surgeon.

*General principles in port placement.* In general, pelvic operations require five abdominal ports, with a sixth optional port if additional access is necessary or if a second patient-side surgeon is available (even for initial training). A schema and corresponding photograph depicting the described standard locations of these ports for transperitoneal pelvic operations are laid out in Figs. 2 and 3, respectively.

A Veress needle (Ethicon Endo-Surgery, Albuquerque, New Mexico) is introduced at a site that is optimal for the primary camera port. This is usually at the supra- or infraumbilical crease in the midline. Pneumoinflation to a pressure of 20 mm Hg is achieved and maintained during port insertion. A higher pressure of 20 mm Hg is

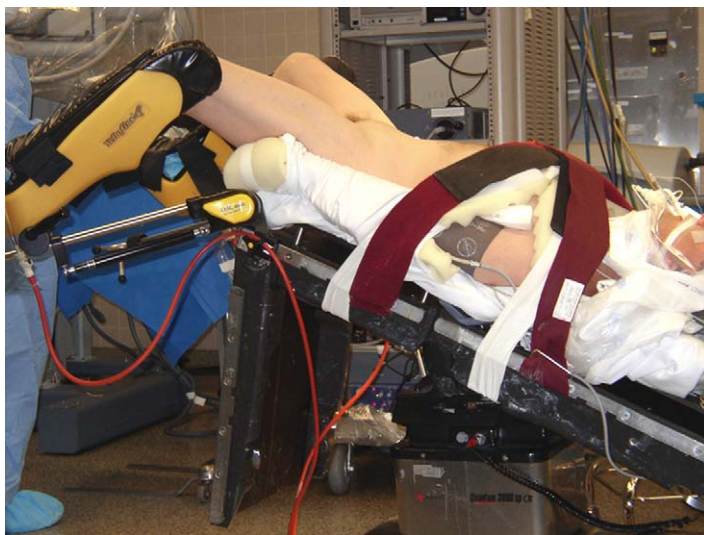


Fig. 1. Patient setup for a pelvic robotic operation before prepping and draping. Note ulnar support padding, hand padding, and crossed thoracic padding.

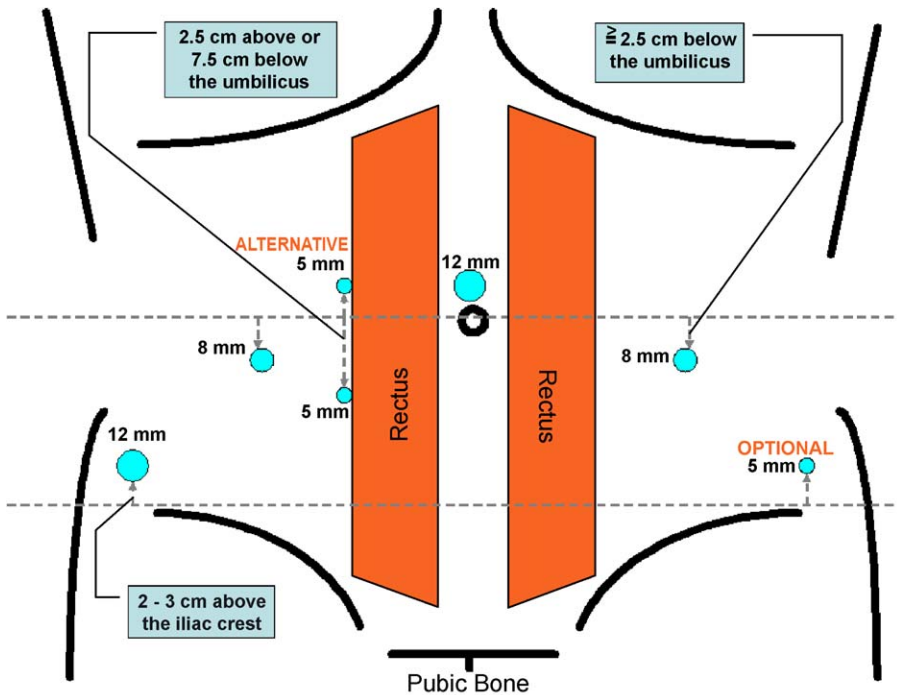


Fig. 2. General principles in port placement for a pelvic operation in relation to key anatomic landmarks.

preferred only during port placement because the additional tension on the abdominal wall yields less when inserting ports, thereby decreasing the risk for inadvertent injury to the viscera. It is not mandatory, however. After all ports are placed, the remainder of the operation is performed at a pneumopressure of 14 to 15 mm Hg, except for periodic verification of hemostasis, when pneumopressure can be reduced to 5 mm Hg.

Once the peritoneum has been insufflated, the Veress needle is replaced with a 12-mm trocar. This is the primary port that eventually will link to the center arm of the robot once it is docked to the body. The three-dimensional da Vinci camera head mounted to the laparoscope is inserted through this port. First, complete peritoneoscopy must be conducted to survey the abdomen for adhesions, estimate bony pelvis dimensions, and note any abnormal anatomic features. If necessary, adhesiolysis should be performed (using 5-mm laparoscopic scissors and dissecting forceps) only enough to enable the placement of both 8-mm robotic arm ports. Any further required lysis of adhesions can be completed subsequently with robotic assistance. The 8-mm da Vinci robotic

ports have been designed to accept 5-mm laparoscopic instruments using the attached adaptable rubber gasket.

At this point, secondary trocars are ready to be inserted and it is important to turn room lights down to enable optimum transillumination of the abdominal wall, thereby avoiding injury to abdominal wall vessels. All team members must keep in mind that injury to abdominal viscera during this step can be avoided by carefully inserting the remaining trocars under direct laparoscopic vision. The authors have found that an upward-directed 30° lens is best for this step.

The next step is to insert both secondary 8-mm ports that correspond to their respective robotic working arms. These two 8-mm da Vinci trocars are placed bilaterally and symmetrically, at least 2.5 cm below the level of the umbilicus and slightly lateral to the edge of the rectus muscle.

The fourth port is a 5-mm port that is used primarily for the suction-irrigator that is operated by the first assistant, who stands on the patient's right side. Therefore, this key port is located between the camera port and the right 8-mm robotic port, but needs to be inserted at a level of

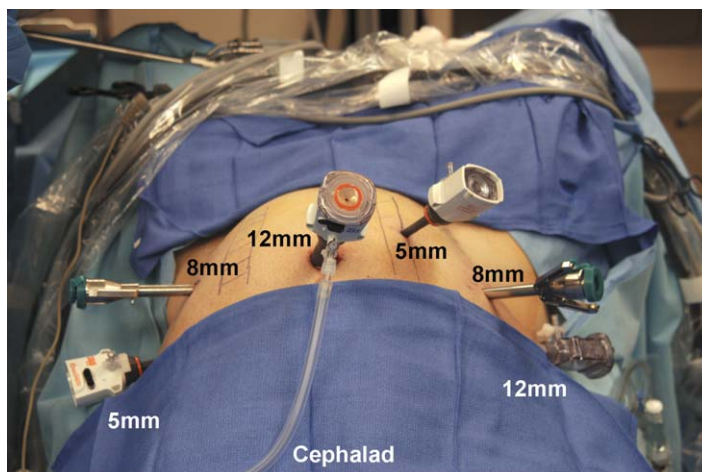


Fig. 3. Spatial anatomy of port placement before installation of the robot for radical prostatectomy.

7.5 cm below or 2.5 cm above the camera port. This is done to prevent the suction from colliding with the camera and ipsilateral robotic arm intracorporeally, as well as to prevent the assistant's hand from colliding with the bulky adjacent robotic arms outside of the body. An additional point of safety regarding this somewhat medially placed port is that the 5-mm laparoscopic scissors, which are used to cut suture throughout the case, should be used exclusively through this port. This is because blind entry with this sharp instrument through other more lateral ports would increase the potential for inadvertent injury to bowel and large vessels because they lie closer to and along the paths of the lateral ports. If insertion of the scissors through the lateral ports is required, it should be performed with great care under constant endovision, remaining cognizant of the directional path of the instrument.

The fifth port is a laterally located 12-mm port that is placed approximately 2 to 3 cm above the right iliac crest along the midaxillary line. This 12-mm port is the dominant conduit for retraction, traction, and countertraction using a 5-mm laparoscopic grasper by the right-sided patient-side surgeon, but is also essential in delivering instruments, such as the Hemo-o-lok clip applicator (Weck Closure Systems, Research Triangle Park, North Carolina) and Endocatch (US Surgical, Norwalk, Connecticut), and for passing or removing suture needles with a laparoscopic needle driver.

If additional retraction is necessary, or a second patient-side surgeon is present, then a 5-mm port

can be placed symmetrically into the left lateral iliac fossa, 2 to 3 cm above the left iliac crest. Direct visual guidance and extreme caution are of paramount importance in placing these two lateral ports because of their lateral location. Trocar insertion should be conducted under a constant and controlled force, in which the assistant pushes gently but pays careful attention to the point of entry into the peritoneal cavity because this is often within 1 to 2 cm of cecum or sigmoid colon.

#### *Radical prostatectomy: transperitoneal approach.*

The patient is padded and positioned as described above. The patient is positioned in a moderate lithotomy with the hips in moderate abduction and knees bent in slight flexion. The table must be set in extreme Trendelenburg position and brought down to its lowest position to prevent bowel from interfering in the operative field. Ports are placed for prostate operations exactly as described above.

#### *Radical prostatectomy: extraperitoneal approach.*

Patient is positioned in the way same as the transperitoneal approach, except that a lesser Trendelenburg position is acceptable.

There are two ways to create extraperitoneal space. First, as described by Gettman and colleagues [1], a 3-cm midline incision is made transversally 1 cm inferior to the umbilicus. The skin is divided down to the anterior rectus fascia and then dissection is performed behind the rectus muscle on either side. Thus, space is created behind the bilateral rectus muscles, separated by

linea alba, which then is divided. Blunt finger dissection is performed to create a large retroperitoneal space.

Second, in the authors' technique, access to the extraperitoneal space is gained by initially making a small 1.5- to 2-cm infraumbilical incision in the midline traversing through skin, subcutaneous tissue, anterior rectus sheath, and linea alba. Thus, the extraperitoneal space is entered, and blunt dissection is performed with the surgeon's finger to create a space to accommodate a preperitoneal distension balloon (PDB 1000, US Surgical). The balloon then is insufflated with air, and, under laparoscopic supervision, the extraperitoneal space is matured enough to permit placement of the 8-mm robotic arm ports. At this point, the PDB is exchanged with a 12-mm blunt-tip trocar (OMS-T1BT, 12-mm, Auto Suture), followed by insertion of both 8-mm robotic trocars under direct vision. Usually, at this juncture the extraperitoneal space is insufficient for placing auxiliary ports for the patient-side surgeon, and therefore the robot should be installed to create more space for additional ports. In this approach, the ports placed are lower than in the transperitoneal approach.

**Bladder operations.** If applicable, the abdomen is marked at the site of the planned stoma, anticipating that this site may be used for the placement of one of the ports.

The patient generally is padded and positioned as described above, except for minor differences. An extended rather than moderate lithotomy position produces the best exposure for a cystectomy. In addition, instead of the maximum incline, Trendelenburg is limited to a 45° tilt for the cystectomy portion of the case. In the case of an orthotopic neobladder, the Trendelenburg tilt subsequently is reduced to 15° to facilitate the neobladder to urethral anastomosis.

Although port-placement techniques for bladder operations are generally the same, there are some minor differences. The Veress needle and subsequent camera port always should be placed supraumbilically to stay above the urachus, thereby allowing adequate visualization during the superior portion of the bladder dissection. The 5-mm suction port should be placed on the right side between the camera and robotic arm as previously described, but should be placed 2 to 3 cm above the umbilicus because this will keep the port well away from the anterior peritoneal fold, which is taken down later with the bladder specimen. Because of the higher placement,

a long-tip suction cannula (bariatric-type) is often necessary to achieve sufficient reach distally.

**Female pelvic operations.** Patient positioning is exactly the same as described above, but only a 30° Trendelenburg tilt is necessary because of the wider female pelvic dimensions.

The placement of ports is almost the same as for bladder surgery, but five ports (one 12-mm and two 8-mm ports for robotic instruments, and a 5-mm and a 10-mm port for a single assistant) are sufficient for these cases.

#### *Kidney operations*

This discussion addresses positioning and port placement with respect to the general approaches for robotic renal surgery. See articles elsewhere in this issue for further discussion of the various categories of kidney operations.

**Transabdominal approach.** After induction of general anesthesia, the patient needs to be placed into a 60° lateral decubitus position to set up for a transabdominal approach. A beanbag, table kidney rest, and table flexion are used for optimal positioning, similar to the traditional setup for laparoscopic procedures. Special attention is paid to ensuring that all pressure points are well padded and that the patient is well secured to the table. Generous use of pillows, an axillary roll, and an arm board are recommended for proper patient positioning. A Foley catheter and oro-gastric tube should be placed before prepping and draping.

Port placement for laparoscopic procedures of the kidney is less straightforward than pelvic procedures because the optimal placement of ports depends on many variables. In addition to obvious considerations such as location of interest (upper pole, lower pole, hilum) or interference of dissection because of large tumor size, the surgeon must also consider potential organ displacement. Because tumor-mass effect, severe hydronephrosis, distorted renal anatomy, and the individual patient's physical features can affect kidney displacement, preoperative radiographic imaging is obligatory in proper planning of surgical approach and port placement.

Pneumoperitoneum is established by way of Veress needle technique followed by a 12-mm primary camera port placed in the midclavicular line, lateral to the rectus muscle and at the level of the umbilicus. It is essential that all subsequent ports be mapped out and placed after the pneumoperitoneum is established. This camera port site can be thought of as a pivot point from which

the subsequent placement of robotic arms can vary depending on the target area of interest. Therefore, if the surgical focus point is upper pole, the two arm ports should be placed more cephalad in relation to the pivot point. For this reason, the two 8-mm robotic arm ports should be placed under vision supervision in equidistant positions (approximately 8–10 cm) from the camera port at right angles to each other, so that the area of interest falls in the central path of this triangular configuration (Fig. 4).

Two additional auxiliary ports (10-mm and 5-mm) are placed to be operated by the assistant. The 5-mm port is placed at the midline just below the xiphisternum and is used for suctioning and liver retraction. The 10-mm port can be placed adjacent to the umbilicus and is used primarily for suction, traction, and retraction, as well as to deploy instruments such as the Hemo-o-lok clip applicator over the vessels or to apply the Endo-GIA stapler (US Surgical).

Alternatively, in thin patients, the camera port may be placed at the umbilicus and the robotic ports positioned accordingly as described previously (Fig. 5). For this setup, the 12-mm port can be placed on the contralateral side of the abdomen.

After port placement, the robot should dock to the patient from the posterior side or with a posterior approach at a 60° cephalad angle with respect to the patient's spine. This is a practical position that will permit the assistant relatively open access to the patient's abdomen from the anterior side and provide an uncompromised robotic position. Once fully docked, both robotic arms can be lateralized manually if further mobilization of the robotic arms is required.

*Extraperitoneoscopic approach.* For retro-peritoneoscopic robotic renal surgery, the patient is

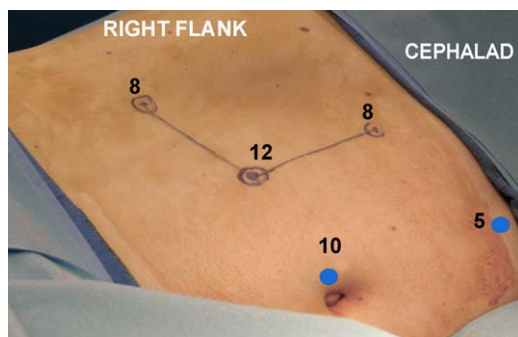


Fig. 4. Sites for placement of ports for transperitoneal right radical nephrectomy with robotic assistance.

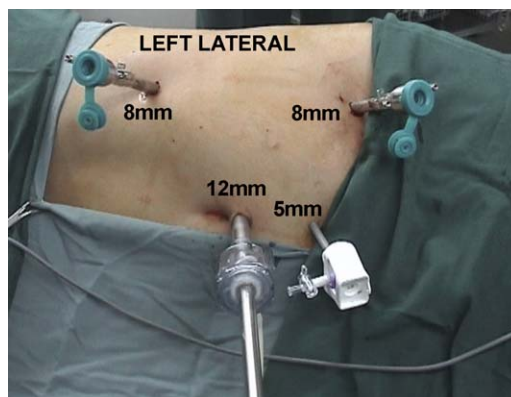


Fig. 5. Alternative port placement for a thin patient undergoing left robotic pyeloplasty.

placed in the lateral flank position with the kidney bridge elevated, and the operating table is bent to widen the space between the costal margin and the iliac crest. The table also is tilted slightly anteriorly, allowing the peritoneum and retroperitoneal space to open, and its contents to fall away anteriorly.

A 1.5-cm incision is made 2 cm below and posterior to the tip of the 12th rib, traversing from the skin down to the thoracolumbar fascia entering into retroperitoneal space. During this step, try to prevent inadvertent dissection between the subcutaneous and muscular planes because the extravasation of gas can result [2]. At this point, this space can be developed with the help of blunt dissection from the finger and later with a laparoscope, or, a small space is created that will accept a trocar-mounted preperitoneal distension balloon (PDB 1000, US Surgical). With this balloon, the space is created under vision and left inflated for 5 minutes to ensure hemostasis before moving on.

After verifying that an adequate working space has been created under laparoscopic vision, the PDB is deflated and replaced with a 12-mm blunt-tip trocar (OMS-T1BT, 12 mm, US Surgical) for placing the robotic camera with a laparoscope. The two additional 8-mm robotic ports are placed subsequently under vision, the robot is installed and used to further broaden the extraperitoneal space, if needed, and the patient-side surgeon's ports are placed. The ports can be arranged in two different manners as per the needs of the patient. The camera port can be placed above the iliac crest in midaxillary line and the two 8-mm robotic arm ports should be placed in equidistant positions

(approximately 8–10 cm) from the camera port at right angles to each other (Fig. 6). Alternatively, the primary camera port can be placed lateral to the quadratus lumborum, and the spatial anatomy of the two robotic ports and patient-side surgeon's port can be changed accordingly (Fig. 7).

#### *Vaso-vasal and vaso-epididymal anastomosis*

The patient is supine on the operating table (Fig. 8) and the robot is installed lateral to the patient. The robot can come from either side and the nurse assistant can stand on the contralateral side.

#### *Nuances, principles, and caveats regarding patient positioning and port placement*

##### *Landmarks*

The most often used landmark for port placement during laparoscopy is the umbilicus. It is an excellent landmark to initiate a transperitoneal procedure and its central location permits general orientation with respect to the abdominal quadrants. In addition, midline fascial convergence generally allows for straight insertion of the Veress needle and port without dissecting various layers of abdominal wall and gives the added benefit of superior cosmesis. For these reasons, it is an ideal site for Veress needle placement and

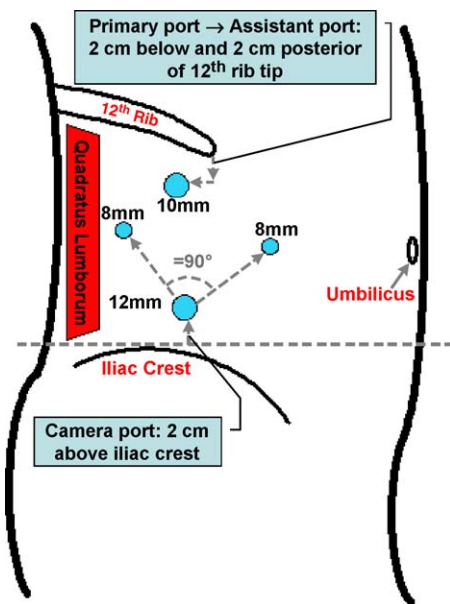


Fig. 6. Port placement for retroperitoneoscopic robotic renal surgery in relation to key landmarks.

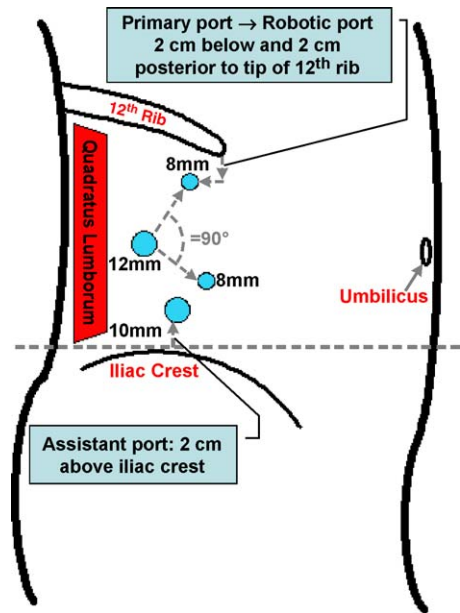


Fig. 7. Alternative port placement for retroperitoneoscopic robotic renal surgery in relation to key landmarks.

subsequent pneumoperitoneum in a patient without prior abdominal surgery. Other important landmarks for robotic surgery include the bony pubis, anterior superior iliac spine, iliac crest, costal margin, and rectus muscle. It is most effective to describe the port placements with respect to these landmarks.

##### *Primary camera port*

The primary camera port should be 12 mm in size because this is the minimum diameter that accommodates the stereoscopic robotic laparoscope. For maximal benefits in vision and perimeter of view, the authors have found that it should be placed near the midline within a 2.5- to 5-cm radius of the umbilicus. If an extraperitoneal approach is being attempted, it is important to have 12-mm blunt-tip trocar available to later convert this to a camera port.

##### *Robotic arm length and span*

The da Vinci robotic arm is 15 cm in length and can articulate up to a maximum working length of 25 cm from the zero point. Therefore, from the entry point of the robotic arm port, the target organ and surgical perimeter must be within the 25-cm arm span limit. If the robot becomes limited by reach, the assistant should

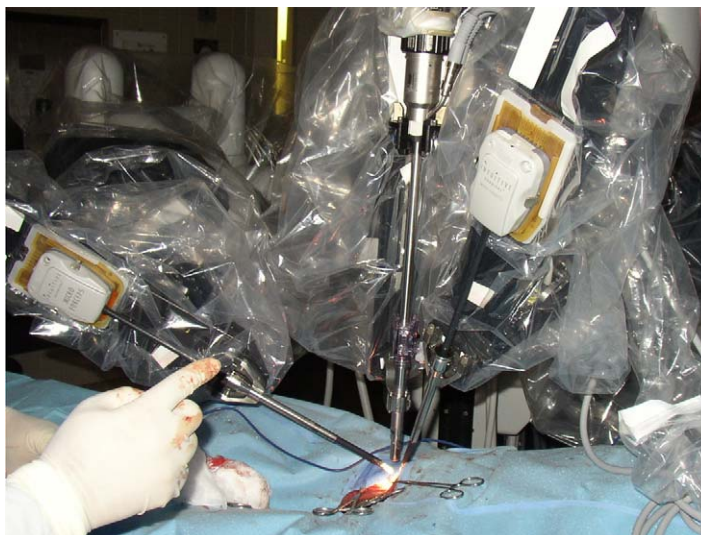


Fig. 8. Recommended patient positioning and robot installation for robotic vaso-vascular anastomosis.

engage the instrument clutch manually to try to insert that arm into the port as far as possible. If this continues to be a problem, the assistant can engage the robotic arm clutch and gently advance the whole robotic arm and port in the needed direction. This needs to be done with great caution and with the instrument removed so as not to cause inadvertent injury. The authors have found this to be an occasional problem when doing urethral anastomosis in a large patient with a deep, narrow pelvis. In such situations, perineal pressure by the assistant is an effective and practical solution.

#### *Interference between adjacent ports*

Because intra-abdominal robotic surgery often requires five or six abdominal ports, port-to-port interference and collisions are problematic. These problems worsen when operating on a petite patient or on a patient with a narrow pelvis. In pelvic operations, if robotic arm ports and lateral ports are placed too far laterally, the robotic arm can collide against the bony pelvis, resulting in limited mobility and significantly hindering the dissection and anastomosis. Conversely, if the ports are placed too medially or if the patient's pelvis is narrow, the robotic arms can collide against the camera, especially when operating deep in the pelvis with the camera zoomed up near the target area.

For these reasons, assessing the patient's size and the bony pelvis is important before placing

any ports. Once the camera port is placed and peritoneoscopy is performed, it is important to assess the pelvic width internally because the external physical examination can be misleading. The optimal position for the da Vinci robotic ports should be 7 to 10 cm away from the camera port to avoid intraoperative collision of robotic arms. The angle between the camera and robotic arm ports should be 90° or greater to provide ergonomically effective maneuverability of the robotic arms.

#### *Subtle variations in port placement according to patient habitus*

Optimum placement of ports varies subtly according to individual patient physical features, such as height, weight, obesity, and patient frame. Patient height generally affects port placement in prostate and bladder cases, in that taller patients should have ports placed lower toward the pelvis to prevent the robotic arm from lacking depth of reach. In comparison, shorter patients require less robotic arm depth and can have ports placed somewhat more cephalad. Although not a hard and fast rule, patients shorter than 1.72 m often are served better by a camera port placed 1 to 2 cm supraumbilically, whereas the taller patients usually have this port placed 1 to 2 cm infraumbilically.

Similarly, wider-framed patients, especially those with a wide, bony pelvis, provide greater freedom in lateralizing ports. This should be done

conservatively, however, to avoid the consequences of overlateralization of ports. In obese patients with a thick abdominal wall, compensation for instrument depth of reach should be accomplished by placing the trocar perpendicular to the skin to prevent traversing obliquely and losing arm length within the preperitoneal fat.

#### *Abdominal distortion secondary to pneumoperitoneum*

One should not decide where the secondary ports will be placed until the peritoneum is insufflated fully because the distension will cause the abdomen to distort in relation to the bony landmarks. In addition, the distance from the skin to the target organ will increase once the abdomen is distended, and this must be taken into account. Thus, skin markings for port placement should be done after carbon dioxide insufflation is completed. The amount of distension is affected by various factors, such as resilience of abdominal wall structures, degree of muscle relaxation, abdominal wall thickness, and abdominal muscle bulk.

#### *Tilt trocar slightly toward the pelvis*

When inserting the trocar, the classic method is to enter at a right angle to the skin. In the authors' robotic pelvic operations, the target area is a long reach from the port site, so it has been helpful to bias slightly toward the midpelvis during trocar insertion. This enables the ports to lie naturally toward the pelvis. The advantage of this is reduced shearing forces on the abdominal wall and fascia, resulting in a smaller fascial defect. Additionally, the natural lie toward the pelvis decreases the risk for bowel and vessel injury during instrument insertion because the port faces an open buffer zone and does not need to be redirected away from the bowels when instruments are changed.

#### *Alternative to the Veress*

If difficulty is anticipated because of significant peritoneal adhesions and abdominal scarring from prior surgery, the Hasson technique of port placement, as described by Binder and colleagues [3], is a safe, effective alternative. A 2.5- to 3-cm minilaparotomy incision is made near the umbilicus, and the primary camera port is placed through this incision. A purse-string-style suture is placed in airtight fashion to prevent gas leakage upon carbon dioxide insufflation. Once pneumoperitoneum is achieved, the remaining ports can

be placed in the usual fashion under direct laparoscopic vision.

#### *One or two patient-side surgeons*

In the authors' experience, these operations can be performed with one patient-side surgeon, except for infertility cases, which can be done alone with a scrub technician.

Because the authors' institution is a training program, two patient-side surgeons are usually at our robotic operations. The new surgeon in the team assumes the left side and assists to a lesser degree but plays a major role in the technical responsibilities during the case, whereas the right-side surgeon provides major assistance. This practice allows the left-side surgeon to observe the intricacies of the case and become facile with the da Vinci setup, function, and troubleshooting. With experience, the left-side surgeon progresses to the right side, and learns the steps and nuances of the operation from further experience and observation.

This article describes the first assistant surgeon as positioned the right side of the patient, but this is not mandatory and can be done from the left if the ports are appropriately adjusted to the left.

#### **Comments**

Different surgeons have used various strategies for placing the ports. Binder and colleagues [3] in their initial experience used subumbilical laparotomy incisions for placing ports under digital guidance during robotic radical prostatectomy. An elegant study by Pick and colleagues [4] concluded that the optimal landmark for port placement in robotic radical prostatectomy should be the pubis, not the umbilicus. In performing pelvic surgery, however, the authors have found various anatomic landmarks (eg, umbilicus, pubic bone, anterior superior iliac spines, iliac crest, costal margin, and rectus muscles) to be important, rather relying on one landmark (umbilicus) or bony landmarks such as pubis bone.

Placement of the first port for the camera is guided by the height of the patient and placement of the two robotic ports is planned following insufflation of the abdomen because its contour changes tremendously and prior-placed marks move. The basic premise is that the area of interest in the pelvis should be reached in a triangular fashion, with the camera port being highest and the two robotic ports at least 2.5 cm below it and

equidistant on either side to avail maximum excursion of the robotic arms.

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## Robotic radical prostatectomy: the European experience

Xavier Cathelineau, MD, François Rozet, MD, Guy Vallancien, MD\*

*Department of Urology, Institut Mutualiste Montsouris, University Paris V,  
42 Boulevard Jourdan, 75014 Paris, France*

“The best way to predict the future is to invent it.”

—Alan Kay

Radical prostatectomy is standard treatment for localized prostate cancer in young patients [1]. The laparoscopic approach is an accepted option for this indication. Although features such as magnification and illumination improve digitally enhanced laparoscopic images considerably, laparoscopic surgery requires acquisition of a new anatomic perspective, hand-to-eye coordination, and the capacity to operate with limited tactile feedback and lack of three-dimensional vision. In addition, surgeons working with the conventional laparoscope have limited dexterity compared with open surgery. The human hand has six degrees of freedom, allowing for complete movement in space, whereas laparoscopic instruments, which are reduced to long sticks with a single joint, have a range of motion limited to four degrees of freedom. These restrictions contribute to the steep learning curve associated with laparoscopy.

The shortcomings of laparoscopy led to the concept that robots may improve the precision and accuracy of anatomic dissection by scaling and filtering surgeon's movements and also may resolve the deficiencies associated with laparoscopy. The feasibility of using a remote-controlled robot to perform urologic procedures is established, especially for radical prostatectomy.

### History

#### *From laparoscopy to robotic surgery*

Operative laparoscopy was developed in gynecology during the 1940s, and then progressively in gastrointestinal surgery from 1986, especially following development of the technique by Muhe in Germany, Mouret in Lyon, and Dubois in Paris.

In 1992, Schuessler and colleagues [2] published the first attempt to perform laparoscopic radical prostatectomy in two cases in an abstract presented to the American Urology Association Congress. In 1997, the same team published nine cases of laparoscopic radical prostatectomy and concluded that this technique did not provide any advantages over open surgery because of the duration and difficulty of the operation, especially when performing the vesico-urethral anastomosis.

In the same year, Raboy and colleagues [3] published a case of extraperitoneal laparoscopic radical prostatectomy. In December 1997, R. Gaston (Bordeaux, France) indicated in a personal communication that he had performed a transperitoneal laparoscopic radical prostatectomy in less than 6 hours.

Six weeks later, Vallancien and Guillonnet started to perform their first radical prostatectomies [4,5]. The main objective was to reduce operative bleeding, postoperative pain, and convalescence time. The surgeons also hoped to be able gradually to ensure preservation of neurovascular bundles, without increasing the oncologic risks of this type of surgery. The step from open to laparoscopic surgery constitutes a completely new experience for the surgeon, who must learn a new endoscopic anatomy and new operative procedures and have to deal with new surgical tools.

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\* Corresponding author.

E-mail address: [guy.vallancien@imm.fr](mailto:guy.vallancien@imm.fr)  
(G. Vallancien).

It requires considerable training in specific laparoscopic skills such as endoscopic suturing and intracorporeal knot tying.

In May 2000, Binder performed the first robot-assisted laparoscopic radical prostatectomy in Frankfurt. Vallancien performed the first robotic radical prostatectomy, included in a training program, at the Vattikuti Institute in Detroit in October 2000, followed by Menon [6] and his team, who developed the technique.

### Operative technique

The surgical console is meant to be “immersive.” The operator, who is not “scrubbed,” operates while seated in front of the master control and looks through binoculars at a three-dimensional image of the operating field. This view is provided by two, parallel, three-chip cameras (InSite, Intuitive Surgical, Sunnyvale, California) and is projected in a way that creates the illusion that the surgeon’s hands are holding the instruments’ tips inside the patient’s body. Lenses of 0° and 30° can be used. The movement of the handles at the console controls the position of the endoscope when the camera footswitch is pressed. The handle movements are processed by the computer software and transmitted to the two

surgical arms manipulating the instruments without measurable delay. Both arms provide three degrees of freedom. At the tip of the instruments, a wrist-like articulation (Endowrist, Intuitive Surgical) enables three more degrees of freedom, and the seventh is for the tool action (eg, scissors blades). The system (da Vinci Surgical System, Intuitive Surgical) allows motion scaling ranging from 2:1 to 5:1 and a 6-Hz motion filter that suppresses human tremor.

Before the patient enters the operating room, the robot is set up. The system is started and performs a self-testing procedure during which it recognizes its spatial position and various other components. The cameras are black-and-white balanced and calibrated. The surgical cart is then draped with sterile plastic sheets. This procedure takes 15 to 30 minutes and can be performed by a nurse.

The operation is performed under general anesthesia. The patient is placed in the supine position with the lower limbs in abduction, allowing the surgical cart to be wheeled in and intraoperative access to the perineum. The upper limbs are positioned alongside the body to avoid the risk for stretch injuries to the brachial plexus.

As with classic laparoscopy, transperitoneal and extraperitoneal approaches can be used for robotic radical prostatectomy (Fig. 1).

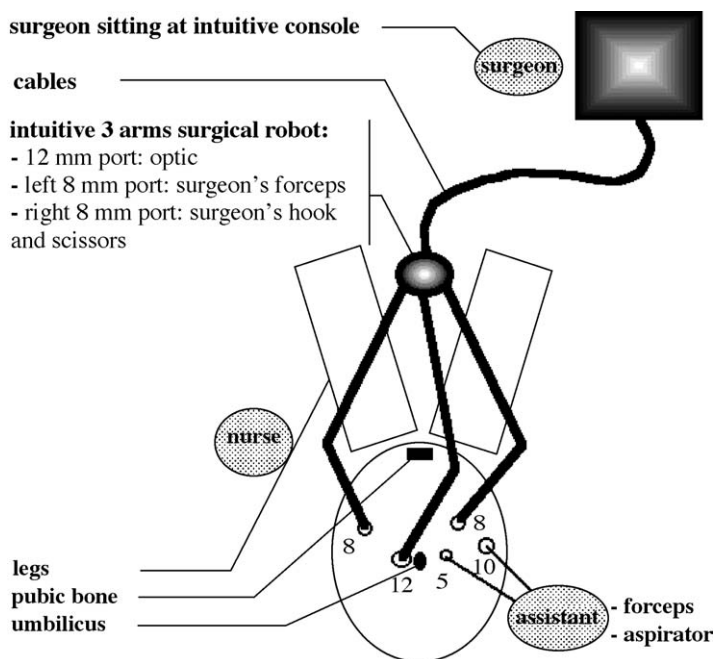


Fig. 1. Installation of the five ports for robotically assisted laparoscopic radical prostatectomy.

### *Transperitoneal approach*

A pneumoperitoneum is created with a veress needle introduced through a left abdominal quadrant puncture, with a maximal pressure of 12 mm Hg. Three trocars are placed in a triangular pattern. A 12-mm port is positioned at the umbilicus for the introduction of the binocular scope. For this procedure, 0° and 30° lenses can be used following individual experience or preferences. Two 8-mm ports used for the instrument arms are placed external to the rectus abdomini muscle, on a line joining the anterior superior iliac spine to the umbilicus.

The robot then is positioned and each arm is docked to its respective port in a fashion that avoids any compression or excessive traction to the patient's skin during the operative movements. Two additional ports are placed in the lower right abdominal quadrant for retraction and suction by the assistant and for the insertion of sutures.

The surgeon (when right-handed) usually has the bipolar forceps in the left hand and the hook or scissors in the right hand.

The operation is performed in the same way as the standard laparoscopic radical prostatectomy, and comprises seven steps:

1. Posterior phase: The posterior parietal peritoneum is incised over the vas deferens, which are sectioned, and the seminal vesicles are dissected completely. The median part of Denonvilliers's fascia is incised until prerectal fat is visible.
2. Anterior phase: The anterior parietal peritoneum is incised from one umbilical artery to the other, providing access to the retroperitoneal space of Retzius after section of the urachus. Once exposed, the pelvic fascia is incised, the puboprostatic ligaments are sectioned, and the prostatic apex is dissected completely.
3. Bladder neck dissection: Vesicoprostatic dissection may be performed with or without preserving the bladder neck. Dissection of the posterior wall provides access to the anterior layer of Denonvilliers's fascia, which must be opened to gain access to the plane of the seminal vesicles and vas deferens already dissected.
4. Dissection of prostatic pedicles and neurovascular bundles: The lateral prostatic pedicles are coagulated selectively with bipolar forceps. The neurovascular bundles are preserved when indicated.

5. Section of the urethra: The dorsal venous complex is ligated and incised. The urethra is dissected away from the apex. The rectourethralis muscle also is sectioned and the prostate is freed completely.
6. Vesicourethral anastomosis: vesicourethral anastomosis is performed with interrupted or running 3-0 vicryl sutures. An 18F Foley catheter is introduced and inflated to 15 mL. A bladder filling with 200 mL saline tests the integrity of the anastomosis; a suction drain is placed in the retroperitoneal space.
7. Extraction of the operative specimen: The prostate is placed in a specimen retrieval bag and removed by enlarging the umbilical incision. Trocar orifices are then closed.

### *Extraperitoneal approach*

Patient positioning and installation of the robot are similar to the transperitoneal approach [7]. The first step is the creation of a prevesical working space. The scope is introduced into the preperitoneal space through a 10-mm trocar placed at the inferior margin of the umbilicus. This optical trocar is used to dissect the space between the two epigastric vessels and the pubic arch. This can be achieved using a classic laparoscope, which is appreciably lighter than the binocular scope of the robot. An insufflation of balloon also can be used for this step. In this approach, higher placement of trocars is useful, especially for the two ports used by the surgeon, to avoid conflict between instruments and the pubic bone. The steps of the procedure are similar to the transperitoneal approach, but in a different order.

First, the fatty tissue is removed from the anterior surface of the prostate, and the pelvic fascia is incised. Bladder neck dissection then is performed, followed by seminal vesicle dissection. Denonvilliers's fascia is incised, releasing the posterior surface of the prostate. The neurovascular bundles are dissected and preserved, depending on anatomic and oncologic conditions. Santorini's venous plexus is ligated, the apex is dissected, and the urethra is sectioned. The anastomosis is performed by interrupted or running sutures.

As with classic laparoscopy, the choice between transperitoneal and extraperitoneal approaches depends on the experience and the intuition of the surgeon.

## Operative data and complications

In June 2001, Abbou and colleagues [8] published their first four cases of laparoscopic radical prostatectomy with a remote-controlled robot. The same year, Pasticier and colleagues [9] reported the experience of the Institut Montsouris after five cases without perioperative complications. The mean operating time was 222 minutes with a mean installation time of 93 minutes. Rassweiler and colleagues [10] also reported their first six cases without intraoperative complications and a mean operative time of 315 minutes.

In 2001, Binder and Kramer [11] published their first cases of robot-assisted laparoscopic radical prostatectomy. Nine patients were operated successfully with a mean operating time of 450 minutes.

After their preliminary experience, these authors concluded that telerobotic laparoscopic surgery was safe and feasible and offered several advantages for the surgeon by enhancing the surgical dexterity, although a learning curve is required with the da Vinci robot. This study also has shown that the telemanipulator facilitated performance of the procedure for surgeons without previous experience in laparoscopic surgery.

Four years after the first robotic radical prostatectomy and these first publications, several teams in Europe and the United States [12–14] have developed the technique and increased their experience.

Of 209 da Vinci systems installed worldwide, 92 currently perform robotic radical prostatectomy: 78 are used in the United States and 14 systems are used in Europe. Approximately 3500 robotic radical prostatectomies have been performed worldwide.

Gettman and colleagues [7] reported their experience on four consecutive patients who underwent extraperitoneal, robot-assisted laparoscopic radical prostatectomy in June 2002. The mean operative time was 274 minutes. The mean blood loss was 1013 mL (range: 550–1500 mL). The mean hospital stay was 5.3 days.

Wolfram and colleagues [15] reported in 2003 their experience on 118 cases, among which only the last 81 were evaluated. The transperitoneal and extraperitoneal approaches were used. The combined ascending and descending technique through the transperitoneal route was chosen in 30 patients, and through the extraperitoneal route in seven patients. A modification of the descending Montsouris technique [5] was performed in 81 patients, for whom the median operating time was 250 minutes (range 150–390 minutes). The median estimated average blood loss was 300 mL (range: 100–1500 mL) with a transfusion rate of 12%. The median time of catheterization was 14 days (range 6–28 d). There were no data available concerning the complications.

After 3 years of experience, 105 robot-assisted laparoscopic radical prostatectomies have been performed at the Institut Montsouris. The first 70 cases were performed by the transperitoneal approach and the last 35 using an extraperitoneal approach. The median operative time was 180 minutes (range 120–290 minutes). The median blood loss was 500 mL (range 150–2000 mL) with a 6% transfusion rate. There were eight complications: one rectal injury (laparoscopic conversion and repair), one sigmoid “erosion” (sutured by one stitch), one extraperitoneal abscess, two hematomas, and three prolonged urinary leaks.

One patient was reoperated to drain the extraperitoneal abscess. There were no deaths, and no pulmonary embolisms. Conversions to classic laparoscopy were necessary because of problems of overweight in two obese patients. Median length of time of hospitalization was 5.5 days (range 3–13 d). The perioperative data are listed in Table 1.

## Oncologic results

The indications for robotic prostatectomy are similar to open or classic laparoscopic radical prostatectomy.

Wolfram and colleagues [15] reported a median preoperative prostate-specific antigen (PSA) level

Table 1  
Perioperative data

Team	No.	Median operating time (min)	Median blood loss (mL)	Median catheterization (d)	Median hospital stay (d)
Frankfurt	81	250	300	14	NA
Montsouris	105	180	500	7	5.5
Créteil	4	274	1013	2.7	5.3

of 8.96 ng/mL (range 1.5–40 ng/mL) in their last 81 patients. Organ-confined disease was found in 68.5% of the patients (pT2), whereas 31.5% were non-organ-confined (pT3). The rate of positive margin was 22% (12.7% for pT2 tumors and 42% for pT3). No data are available concerning the postoperative PSA levels.

In the Montsouris experience of 105 cases, the median preoperative PSA level was 8 (range 4–24). The median Gleason score was 6.5. There were 71% of organ-confined tumors (pT2) and 29% of non-organ-confined tumors (pT3). The positive margin rate was 22% (11.7% for pT2 tumors and 43% for pT3 tumors). Postoperative PSA levels were less than 0.2 in 98% of patients. The pathologic stage and margin status are listed in Table 2.

### Discussion and perspectives

With more than 900 procedures performed, the Vattikuti Institute has the largest experience of robotic radical prostatectomy in the world. The Institute has reported a prospective comparison of radical retropubic prostatectomy (RRP) and robot-assisted anatomic prostatectomy (RAP) [16] comparing 30 consecutive patients undergoing conventional RRP and 30 initial patients undergoing RAP in the same department. The preoperative parameters were comparable in the two groups. The mean operating time was 2.3 hours for RRP and 4.8 hours for RAP ( $P < .001$ ). The mean blood loss was 970 mL for RRP and 329 mL for RAP ( $P < .001$ ). The mean pain score at postoperative day 1 was 7 in RRP patients and 4 in the RAP group. After this initial experience, the authors concluded that, “RAP is a longer procedure than RRP. However, the blood loss is minimal and patients feel less pain and are discharged early from the hospital.”

One year later, the same team published its results of 250 robotic radical prostatectomies [17]. The mean operative time was 160 minutes and the

mean blood loss was 153 mL. No patient required transfusion. As for the classic laparoscopic approach, this study underlines the role of the “learning curve” in such a technique.

Finally, these results are comparable to those of the European teams in length of operative time and morbidity, but blood loss is higher with the robotic approach than with classic laparoscopy in the experience of the Montsouris Institut (500 mL with robotic, 300 mL with laparoscopy). This experience underlines that the instruments need to be improved to obtain similar consistency as in the classic laparoscopic approach (especially improvement of the tissue grip on bipolar forceps and the necessity of providing monopolar coagulation on scissors).

Moreover, these data confirm equivalent results between extraperitoneal and transperitoneal routes for the robotic or the classic laparoscopic approach.

### Present and future

Given the difficulty involved in the operation of laparoscopic radical prostatectomy, telerobotics has generated significant interest among urologists who aim to reproduce and improve the technique [18]. Some authors advocate the use of these computers, fundamentally different from “real robots,” because it could offer advantages.

The frequently reported benefits are reduced blood loss, smaller incisions, and quick postoperative recovery. These, however, have to be credited to the nature of the laparoscopy itself and not to the computer-assisted surgery.

The other reported advantages are dexterity enhancement in the manipulation of the instruments and improved vision. Three-dimensional imaging and restitution of all degrees of movement to the surgeon could be appropriate tools to facilitate training for minimally invasive surgery and to lessen the learning curve associated with these technically demanding procedures. The three-dimensional vision provided by a dual scope

Table 2  
Oncologic results

Team	No.	Preoperative PSA	Stage	Positive margin/pT2	Positive margin/pT3
Frankfurt	81	8.9	68.5% pT2 31.5% pT3	12.7%	42%
Montsouris	105	8	71% pT2 29% pT3	11.7%	43%

is extremely precise, but is not specific to remote-controlled surgery. Moreover, it is an indispensable tool of telemanipulators because it is the only way for the operator to know the exact position of the instruments in the operative field.

One of the significant benefits for the surgeon is a reduction of the fatigue accompanying difficult procedures. The robotic device provides a good ergonomics for the surgeon, whose forearms are supported to allow precise manipulation of the joysticks. A possible reduction of the amplitude of displacement of the remote-controlled arms and the six degrees of freedom, allowing rotation of the remote-controlled needle holders in all directions, makes suturing easy.

Improvement of the surgical technique has allowed a reduction of the morbidity of radical prostatectomy. The development of laparoscopic radical prostatectomy has demonstrated the feasibility of a mini-invasive removal of a pelvic organ that is poorly accessible. Moreover, it has shown the possibility of a reconstructive procedure in this difficult area: the urethra-vesical anastomosis.

The benefits for patients that could be expected from telemanipulation of surgical instruments remain unclear when regarding operative time, postoperative course, and functional results. Considering the average operating time for conventional laparoscopic radical prostatectomy in experienced hands, the authors do not believe that the use of the telemanipulation technology will reduce operative time significantly. The dissection of the neurovascular bundles does not seem to be more precise with robotic assistance than in classic laparoscopic technique. Although the urethra-vesical anastomosis seems easier with a telemanipulator for the surgeon who does not have enough experience with intracorporeal suturing, it will be difficult to improve on the quality of the anastomosis performed by experienced laparoscopic surgeons.

Robotic telesurgical systems have considerable shortcomings that need to be overcome. The major limitation to their widespread use in the operating rooms is the cost of available systems and machines. Instruments also are costly and need to be replaced frequently because they can be re-used only a few times. As the trend of component miniaturization continues, it is expected that future systems will be more user-friendly with less cumbersome arms. Another important drawback of these machines is the lack of sensitivity, making accurate dissection difficult. New robotic devices

should incorporate tactile feedback, allowing the surgeon to feel changes in grip strength or tissue texture.

New developments in robotic surgical systems concern:

- 5 mm-diameter instruments with more optimal articulation: snake wrist
- Four-armed da Vinci system allowing solo surgery
- Arms installed directly in the operating room, coming from the roof, not on a surgical cart
- New three-channel scope allowing stereo three-dimensional vision and a panoramic view (the third channel is similar to a fish eye)

It is hoped that with the evolution of enhanced and virtual reality software, more lifelike simulations will become available to improve surgical training. Moreover, with digital imaging studies depicting specific anatomic defects or pathologies (three-dimensional CT), patient-specific simulations may give surgeons the opportunity to practice a specific endoscopic procedure in virtual reality before performing the actual operation [19].

The last point to discuss is the future of “industrial robotic surgery.” The authors believe that a senior surgeon could control two, three, or four robotic laparoscopy prostatectomies at the same time; these operations could be done in a large amphitheater with one or more anesthesiologists, one circulating nurse, four scrub nurses at the tables, and four resident at the consoles. Such an organization is feasible with a senior surgeon using the joysticks when necessary.

### Further readings

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# Vattikuti Institute prostatectomy, a technique of robotic radical prostatectomy for management of localized carcinoma of the prostate: experience of over 1100 cases

Mani Menon, MD, FACS<sup>a,b</sup>, Ashutosh Tewari, MD<sup>a</sup>,  
James O. Peabody, MD<sup>a</sup>, Alok Shrivastava, MD<sup>a</sup>,  
Sanjeev Kaul, MD<sup>a</sup>, Akshay Bhandari, MD<sup>a</sup>,  
Ashok K. Hemal, MD, MCh, FACS<sup>a,\*</sup>

<sup>a</sup>Vattikuti Urology Institute, Henry Ford Hospital, 2799 West Grand Boulevard, K-9, Detroit, MI 48202-2689, USA

<sup>b</sup>Department of Urology, Case Western Reserve University, 11000 Euclid Avenue, Cleveland, OH 44106-4931, USA

Prostate cancer is the commonest cancer in males in the United States, accounting for 33% of all newly diagnosed cancers in men. Of prostate cancer cases diagnosed in 2004, 86% are expected to be local or regional, for which 5-year survival rates equal 100% [1]. It is estimated that in 2004 in the United States, 230,110 new cases of prostate cancer will be diagnosed and 29,900 people will die from the disease [1]. Radical prostatectomy reduces disease-specific mortality in patients who have localized prostate cancer, but many men seek other treatments because of the invasiveness of surgery and the resultant side effects [2]. In 1982, Walsh [3] laid the foundations of contemporary anatomic radical retropubic prostatectomy based on his earlier work delineating the anatomy of the dorsal vein complex and the cavernosal nerves.

Patient acceptance of surgical procedures increases with the development of minimally invasive surgical techniques, even in the absence of randomized clinical trials showing substantial advantages to these approaches [4]. Because of this, urologists have endeavored to develop techniques of laparoscopic radical prostatectomy (LRP) [5].

LRP is performed commonly in Europe [6–8], but less so in the United States [9–11], perhaps because “open” surgeons find the technique difficult to master [12]. This technique, with its decreased invasiveness, translates into shorter hospital stay, decreased pain, and earlier resumption of normal activities for the patient. In expert hands, this technique is safe, quick, and provides outcomes comparable to open surgery with less blood loss and less postoperative discomfort [13–16].

These pioneers, however, also have raised a warning: LRP has a steep learning curve and only individuals with advanced laparoscopic expertise should undertake it. Laparoscopy has certain limitations: counterintuitive movements, rigid instruments, two-dimensional images, and limited ergonomics [17]. Although these can be overcome with practice, they still relegate complex reconstructive procedures to the realm of a few brave surgeons.

## Development of robotic radical prostatectomy (RRP)

The authors often are asked what caused us to develop techniques of robotic prostatectomy. Serendipity and a lack of sophisticated laparoscopic skills are the two most probable reasons. The authors began by trying to establish a pure

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\* Corresponding author.

E-mail addresses: [akhemal@hotmail.com](mailto:akhemal@hotmail.com)  
[ahemal@hfhs.org](mailto:ahemal@hfhs.org) (A.K. Hemal).

laparoscopic radical prostatectomy program under the guidance of and formal collaboration with Guillonnet and Vallancien of Montsouris, but rapidly learned that Menon (at least) was untrainable. Because the authors were reasonably comfortable with the Walsh-Lepor approach to open radical prostatectomy [4,18], they hypothesized that robotic assistance would help. Menon had seen the da Vinci Surgical System at Montsouris and was encouraged by the French surgeons to try it in Detroit [19].

Based on the preliminary work of Abbou, Binder, Pasticier, and colleagues, in 2001, the authors' team introduced an anatomic approach to the radical prostatectomy with robotic assistance [19–21]. In previous reports, the authors showed that robotic assistance enhanced one's ability to perform a RRP, enabling results comparable to those of leaders in the nonrobotic LRP with greater laparoscopic experience [22–24]. These findings have been confirmed by other groups who are familiar with principles of anatomic radical prostatectomy to perform robotic prostatectomy, but have minimal laparoscopic experience [25,26].

### **Technique of Vattikuti Institute prostatectomy (VIP)**

The authors began performing LRP in October 2000 and robotic radical prostatectomy in March 2001, and have done over 1100 robotic radical prostatectomies. Initially, the authors performed robotic radical prostatectomy by duplicating the steps of the Montsouris approach of LRP, but soon modified the technique to reflect the experience gained from "open" surgery, incorporating many of the steps of conventional radical retropubic prostatectomy. The authors' current approach—Vattikuti Institute Prostatectomy (VIP)—is based on the palimpsest of conventional, anatomic "open" prostatectomy, melded with knowledge from laparoscopic prostatectomy, and overwritten with the technical nuances of robotic technology [27,28]. The VIP combines the techniques of a transperitoneal approach (a large working space) with those of an extraperitoneal dissection. The authors describe the technique in detail, highlighting useful tricks.

#### *Patient selection: indications and contraindications*

The authors' indications for the VIP are identical to those for open radical prostatectomy:

patients who have localized prostate cancer, biologically significant disease, and a life expectancy of over 10 years. The authors recommend surgery to patients who have nonfocal Gleason-6 and higher cancer and a Charlson comorbidity score of less than 3. Thus, 80% of patients have a Gleason score of 7 to 9. Approximately 30% of cases have had previous laparotomy. The authors have found that open radical prostatectomy is sometimes difficult in patients who have had laparoscopic inguinal herniorrhaphy with mesh, but this poses no problem for VIP. Relative contraindications for VIP include a history of ruptured viscera and peritonitis, but 2% of the authors' patients fall into this category. The operation is more difficult in patients who are markedly obese (body mass index greater than 40), in those who have undergone radiation or androgen-deprivation therapy, and in those with a history of transurethral or suprapubic prostatectomy. Large-volume prostates (greater than 100 g), large median or lateral lobes, or an android (narrow) pelvis may lead to a difficult dissection.

#### *Preoperative preparation*

The authors' usual recommendation is to wait at least 6 weeks after prostatic biopsy. Discontinuation of aspirin and antiplatelet agents is required for at least 2 weeks before surgery because even slight bleeding obscures vision and makes the dissection imprecise. Antibiotic prophylaxis is given before surgery per hospital protocol. A combination of compression stockings and subcutaneous heparin, 5000 units, is used pre- and postoperatively during the hospital stay. A mechanical bowel preparation is not necessary, but it is preferable to maintain a clear liquid diet and use a laxative 1 day before surgery.

#### *Anesthesia*

VIP is done under general endotracheal anesthesia using halogenated gases (ie, isoflurane) as opposed to nitrous oxide, which may give rise to abdominal distension. It is suggested to restrict intravenous fluids to 600 to 800 mL until anastomosis is performed. This step avoids excessive production of urine during the surgery, therefore needing fewer suction maneuvers to clear the field.

#### *Patient's position*

The patient is supine with both arms at his sides to avoid the risk for brachial plexus injury. A

thoracic wrap padded with foam is preferred to cover the shoulders and upper chest. The patient is positioned in moderate lithotomy with the legs separated in flexion and abduction and a foam support under the buttocks. The legs' separation in lithotomy position helps in bringing the robot between the legs. Adequate padding of all pressure points is mandatory. The table is set in extreme Trendelenburg position and fully down. Fig. 1 shows the typical operating room set-up. After the patient is prepped and draped, a Foley catheter is placed into the bladder and an orogastric tube is placed.

### *Surgical technique*

The operation is performed using the da Vinci Surgical System (Intuitive Surgical, Sunnyvale, California).

### *Pneumoperitoneum and placement of ports*

A Veress needle (Ethicon Endo-Surgery, Albuquerque, New Mexico) is introduced from a supra- or infraumbilical incision for pneumoinsufflation to a pressure of 20 mm Hg. This pressure is maintained while inserting the ports, but is decreased to 14 to 15 mm Hg for the remainder of the procedure; hemostasis is ensured with 5-mm Hg pneumopressure at the end of the procedure. The Veress needle is replaced with a 12-mm trocar, the three-dimensional da Vinci laparoscope is inserted, peritoneoscopy is conducted, and if adhesions are observed, adhesiolysis is performed following placement of secondary ports.

Four other trocars are placed under laparoscopic vision (to transilluminate the abdominal wall to avoid injury to vessels in the abdominal wall and see intra-abdominal entry to prevent potential injury to abdominal viscera). Two 8-mm da Vinci trocars are placed 2.5 cm below the level of the umbilicus, pararectally on either side. A 5-mm trocar is placed between the umbilicus and the 8-mm port on the left or right side, depending on the assistant's choice and his or her dominant hand. A 12-mm port then is placed in the midaxillary line on the left or right side depending on the first assistant's position, approximately 2.5 cm above the iliac crest. If the second assistant is helping in the procedure (for orientation or training purposes), then a 5-mm trocar is placed in the ipsilateral iliac fossa symmetrical to the location of the 12-mm port in contralateral iliac fossa. The spatial anatomy of port placement also is changed according to the height and body stature of the patient (Figs. 2 and 3).

### *Peritoneoscopy*

Because approximately 30% of the authors' patients have undergone prior abdominal surgery, most need lysis of adhesions before placement of secondary ports. In previously operated cases, after placement of the first port, inspection of the abdominal cavity often reveals adhesions. In 5% to 10% of patients, adhesions are seen even in the absence of previous abdominal surgery. These adhesions are lysed by the patient-side assistant using conventional laparoscopic instruments to make room for the placement of the secondary

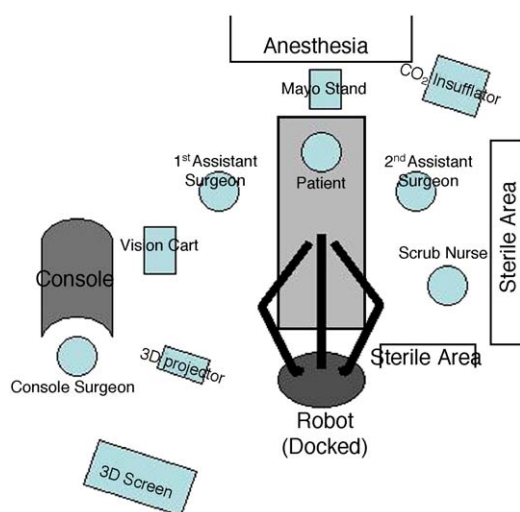


Fig. 1. Operating room set-up.

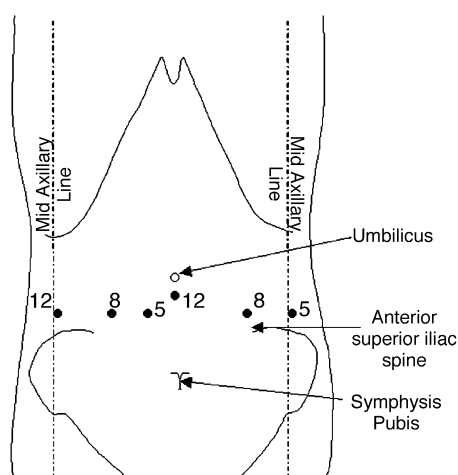


Fig. 2. Schematic diagram of port placement in a tall (greater than 1.78 m) individual.

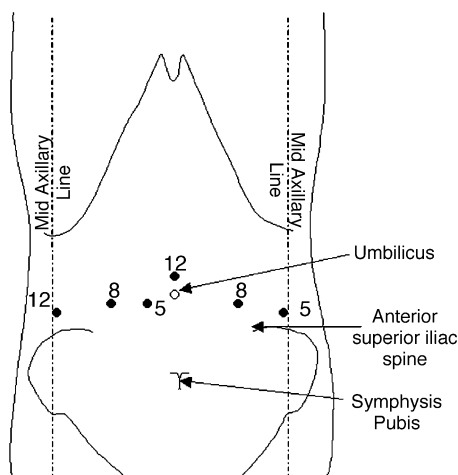


Fig. 3. Schematic diagram of port placement in a short (less than 1.73 m) individual.

ports (Fig. 4). Care is taken with leftover adhesions, however, during subsequent dissection with robotic instruments.

#### *Robotic and laparoscopic instruments*

Robotic instruments are expensive, and the authors use as few as possible. The minimum required is the da Vinci long-tip grasper, a hook, and two needle holders. The authors also regularly use the articulated da Vinci bipolar coagulating forceps and cold scissors to perform the nerve-sparing part of the procedure, apical dissection and division of the urethra, and bilateral pelvic lymphadenectomy in these patients. Tables 1 and 2 give a detailed description of robotic and laparoscopic instruments and their uses. Box 1 lists the various steps of the VIP using the da Vinci Surgical System.

#### *Entry into the space of Retzius*

The entry into the space of Retzius is done with a 30° angled lens looking upward. Because the patient is in the extreme Trendelenburg position, the small bowel usually falls away, but one usually needs to take down adhesions between the sigmoid colon and the posterior peritoneum to make more room, which will be needed during lymphadenectomy. The extraperitoneal space is entered through an inverted, U-shaped incision on the parietal peritoneum, superior to the dome of the bladder and lateral to the medial umbilical ligaments. It is important to perform dissection lateral to the medial umbilical ligaments because it opens more space for subsequent bilateral pelvic

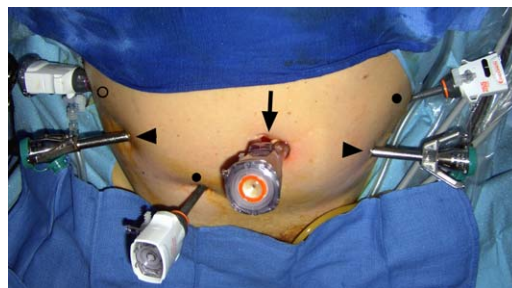


Fig. 4. Port placement. A 12-mm camera port (black arrow) at the level of umbilicus, other 12-mm port (hollow circle) in midaxillary line 2.5 cm above the right superior iliac crest, two 8-mm ports (arrowheads) for robotic arms placed 3 to 5 cm below the level of umbilicus lateral to rectus muscle on either side, a 5-mm port (solid black circle) is placed in left iliac fossa 5 cm above and lateral to anterior superior iliac spine for assistance, and the other 5-mm port (solid black circle) is placed on the right side between the camera port and the right robotic port for the suction cannula.

lymphadenectomy. The internal inguinal ring can be seen medial to the external iliac vessels, which are covered by a lateral fold of the peritoneum. The vertical limb of the peritoneal incision is made lateral to the medial umbilical ligament, and medial to the internal inguinal ring. The vas deferens is seen coursing obliquely across the incision and can be retracted out of the operating field or divided before further dissection. When the inferior portion of the vertical limb of the peritoneal incision is deepened, the pubic bone is seen as an anatomic landmark and the iliac vessels lie laterally. The incisions are joined anteriorly, dividing the bilateral medial umbilical ligaments and urachus, and then the bladder is dissected off the anterior abdominal wall to enter into the space of Retzius (Fig. 5).

#### *Control of the dorsal venous complex*

Once the anterior surface of the bladder is exposed, the authors try to clean off the fat near the apex and over the prostate. The superficial dorsal vein over the prostate is coagulated and divided. As in regular surgery, endopelvic fascia is opened on either side from the semilunar gap to the prostatovesical junction, identified by the presence of a tongue of extravascular fat. Currently, this step is being modified so that endopelvic fascia is not opened and subsequently becomes part of the prostatic fascia. This reveals the puboprostatic or pubovesical ligaments.

Table 1

Use of three-dimensional-endoscopes, instruments and other accessories during different steps of Vattikuti Institute prostatectomy (VIP)

Steps of Vattikuti Institute prostatectomy	Use of different endoscopes during surgery	Use of different Endowrist instruments during surgery	Comments
Patient positioning	—	—	Lithotomy, steep Trendelenburg, arms tucked by the side, strapped
Placement of ports	30-degree angled up	—	—
Peritoneoscopy, laparoscopic adhesiolysis	30-degree angled up and down	—	Approximately 30% of patients have a history of previous surgeries and require adhesiolysis
Release of sigmoid colon on left and cecum on right (if needed)	30-degree angled up	Long-tip forceps, permanent cautery hook	—
Mobilization of bladder and creation of space of Retzius	30-degree angled up and 0 degree	Long-tip forceps, permanent cautery hook	—
Incision of endopelvic fascia, delineation of prostatovesical junction, apical dissection	0-degree	Long-tip forceps, permanent cautery hook	—
Control of dorsal vein complex, application of stay suture	0-degree	Large needle drivers	0-Vicryl (Polyglactin 910) suture on a CT-1 (36-mm, taper) needle (Ethicon)
Bladder neck transection (anterior and posterior wall)	30-degree angled down	Long-tip forceps, permanent cautery hook	—
Vas deferens and seminal vesicle dissection	30-degree angled down	Long-tip forceps, permanent cautery hook	—
Incision of Denonvilliers' fascia, and posterior dissection	30° angled down	Long-tip forceps, permanent cautery hook or PreCise bipolar forceps, round-tip scissors	—
Control of prostatic pedicles	30° angled down	PreCise bipolar forceps, round-tip scissors	Usually dissect vascular prostatic pedicles and control with bipolar cautery; occasionally Hem-o-lok clips are used
Preservation of nerves (a) veil of Aphrodite (lateral prostatic fascia)	30° angled down	PreCise bipolar forceps, round-tip scissors	—
(b) standard nerve sparing			
Apical dissection and transection of urethra	0°	PreCise bipolar forceps, round-tip scissors	Specimen bagged in EndoCatch bag
Bilateral pelvic lymph node dissection	0°	PreCise bipolar forceps, round-tip scissors	—
Bladder-neck reconstruction (if needed)	0°	Long-tip forceps, large needle driver or two needle drivers	(a) 2-0 Vicryl (Polyglactin 910) suture on and RB-1 (17-mm taper) needle.
Urethrovesical anastomosis	0°		(b) Two, 3-0 Monocryl (Poliglecaprone 25) sutures on an RB-1 (17-mm taper) needle (Ethicon). One dyed and one undyed.

Table 2  
Instruments and accessories used for Vattikuti Institute prostatectomy

Accessories	Manufacturer	Comments
Veress needle	Ethicon, Endo-Surgery	Used for establishing pneumoperitoneum
Robotic ports	Intuitive Surgical	Reusable, used for docking robotic arms, 8 mm
Endopath dilating tip trocar with sleeve (12 mm)	Ethicon Endo-Surgery, Cincinnati, Ohio	Disposable, used only in obese individuals, 150 mm long, 12 mm diameter
Endopath bladeless trocar with sleeve (12 mm)	Ethicon Endo-Surgery	Disposable, camera port 100 mm long, 12 mm diameter
Endopath bladeless trocar without sleeve	Ethicon Endo-Surgery	Disposable, assistant port 5 mm diameter
5-mm trocar sleeve (long)	Gibbons Surgical Corp, Virginia Beach, Virginia	Reusable
12-mm trocar sleeve (long)	Gibbons	Reusable
Endopath needle holder	Ethicon Endo-Surgery	Reusable
Renewcut II micro scissors	OR Specialty	Scissor tip disposable, handle reusable
Atraumatic forceps	Medtronic-Xomed, Minneapolis Minnesota	Reusable
ACMI long suction tip	ACMI/Circon, Southborough, Massachusetts	Reusable, 48 cm long
Endopouch Retriever	Ethicon Endo-Surgery	Disposable, 26 cm long, 10 mm diameter
Hem-o-lok MLX endoscopic applier	Weck Closure Systems, Research Triangle Park, North Carolina	Reusable, 32 cm curved, 10 mm diameter
Codman Cottonoid	Johnson & Johnson, New Brunswick, New Jersey	Disposable, 2.5 × 15 cm

Small perforating veins between the prostate and the levator ani must be cauterized. The authors avoid dividing the puboprostatic ligaments and dissect the urethra as little as possible. This approach has improved the time to total continence dramatically, which has averaged 42 days for the last 800 patients. The deep dorsal vein complex is ligated with a single vertical mattress suture (0-vicryl on CT-1 needle). This suture is passed horizontally in the groove between the urethra and the dorsal vein complex, and then backward under the most superficial fibers of the puboprostatic ligament (Fig. 6).

A second suture is placed on the anterior surface of the prostate. The ends of this suture are left 3 cm long so that the assistant can grasp it and apply traction on the prostate during division of the bladder neck and urethra. An attempt is made to separate neurovascular bundles and the rectourethralis muscle from the posterior surface of the urethra using blunt dissection with the da Vinci needle holders, much as the urethra is pinched off with the fingers during open prostatectomy. This is a crucial step because it facilitates

dissection of the posterior apex and urethral transection at a later stage. The authors do not perform this step in every patient, however, and it is left for the time of urethral transection.

#### *Division of the bladder neck*

Division of the bladder neck is done with a 30° angled lens directed downward. Many laparoscopic surgeons consider identification of the bladder neck one of the most difficult parts of the operation. Several subtle maneuvers can be used to aid this, however. At the midline, the bladder muscle and the prostate are in immediate contact because the bladder mucosa is continuous with the mucosa of the prostatic urethra. A distinct plane can be developed between the bladder and the prostate laterally, however, where fibroareolar and fatty tissue bridges the distance between the prostate and the bladder. Under traction, this distance can be almost 2 cm.

Therefore, the authors start the bladder neck dissection laterally, at the junction of the lateral and posterior surfaces of the prostate. The left assistant pulls the prostatic suture firmly while this is done.

**Box 1. Steps of Vattikuti Institute prostatectomy**

1. Position of the patient
2. Placement of the ports
3. Peritoneoscopy, lysis of adhesions, and release of sigmoid colon and cecum
4. Mobilization of the bladder and opening of space of Retzius
5. Incision of endopelvic fascia, delineation of prostate-vesical junction, apical dissection, control of dorsal vein complex, and application of stay suture
6. Bladder-neck transection (anterior and posterior window)
7. Dissection of vas deferens and seminal vesicles
8. Incision of Denonvillier's fascia and dissection posterior to apex of the prostate
9. Control of prostatic pedicles
10. Preservation of neurovascular bundle: (a) preservation of lateral prostatic fascia, (b) preservation of regular neurovascular bundle
11. Apical dissection and transection of the urethra
12. Bilateral pelvic lymph node dissection
13. Urethrovesical anastomosis
14. Check the patency of the anastomosis and placement of drain
15. Final outcome (after removal of specimen by extending incision at umbilical port and closure of ports)

This, aided by the downward-looking lens and the three-dimensional vision, usually is adequate to identify the prostatovesical junction. The authors also have noticed that soft fatty tissue demarcates the prostatovesical junction at its posterolateral surface. The inflated balloon inside the bladder is not of great aid in the identification, and may lead astray a naïve surgeon by directing the dissection to the midline and more toward the bladder. If the proper plane is entered, dissection will encounter fibrofatty tissue and little bleeding. On the other

hand, if dissection is too close to the prostate, fibromuscular tissue that bleeds will be seen.

As the dissection is deepened in the anterior midline, the tip of the Foley catheter will be seen (Fig. 7). The Foley balloon is deflated and the tip of the catheter is pulled toward the ceiling by the assistant. The posterior bladder neck is divided in the midline at the prostatovesical junction, which can be identified precisely. The incision varies according to the presence of median lobe, large lateral lobes, and intravesically projecting lobes of

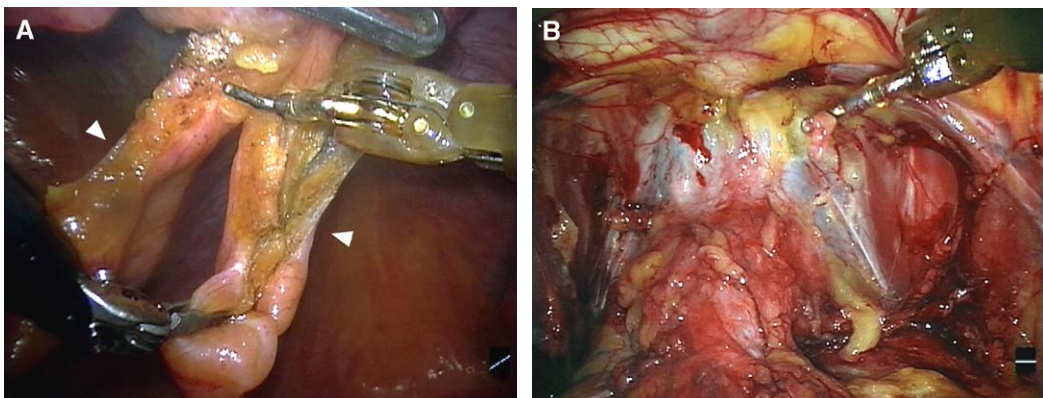


Fig. 5. (A) The bladder is being dissected from the anterior abdominal wall. Urachus (arrowheads) is being divided with the help of hook, subsequent to the division of right and left medial umbilical ligament. (B) Space of Retzius endopelvic fascia (below the tip of hook) and perinealis muscle are seen bilaterally, and glistening pubic arch can be seen on the top.

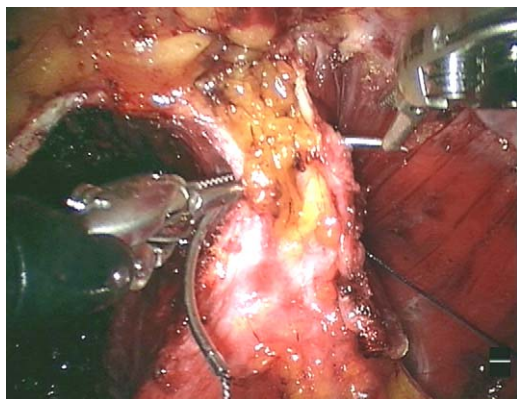


Fig. 6. Ligation of deep dorsal vein complex with preservation of puboprostatic ligament (needle can be seen being passed underneath the ligaments).

the prostate [29]. After the full thickness of the detrusor muscle has been divided, dissection is extended laterally, maintaining a clean detrusor margin for the subsequent vesicourethral anastomosis. In patients with a median lobe, its delivery outside the bladder helps in the incision and dissection of the posterior bladder wall from the prostate.

*Dissection of the vas deferens, seminal vesicles, and prostatic pedicles and incision of Denonvillier's fascia*

This part of the dissection is done with a 30° lens directed downward. Division of the posterior bladder neck and incision of the anterior layer of Denonvillier's fascia leads to a window (see Fig. 7)

from where the ampulla of vas deferens and seminal vesicles can be dissected and pulled up [30]. The vasal and seminal vesicular arteries (sometimes several) can be seen clearly and should be coagulated. Both seminal vesicles are freed before commencing the dissection of the prostate. In some cases, the tips of the seminal vesicles are left intact to preserve potency better, but in such instances, the authors obtain frozen sections from the transected margins of the seminal vesicles.

If a regular, nerve-sparing operation is contemplated, the prostatic pedicles are dissected on either side, and divided between two hem-o-lok clips. Alternatively, the vessels are dissected with the help of the da Vinci bipolar forceps and divided with the da Vinci articulating scissors. The authors do not divide the prostatic pedicles if the intent is to preserve the prostatic fascia. The seminal vesicles are lifted anteriorly to demonstrate the longitudinal fibers of the posterior layers of Denonvillier's fascia near the base of the prostate. The fascia is thick and has several layers in this location. It is incised sharply until prerectal fat is seen. The authors avoid the use of electrocautery for the entire posterior dissection so that the neurovascular bundles are not damaged by conducted heat. Once the proper plane is entered, the authors dissect between the layers of Denonvillier's fascia to leave a protective layer of fascia over the rectum and any network of nerves in this area.

*Nerve-sparing (standard and prostatic fascia)*

Animal and human studies suggest that accessory cavernosal nerves may run underneath the

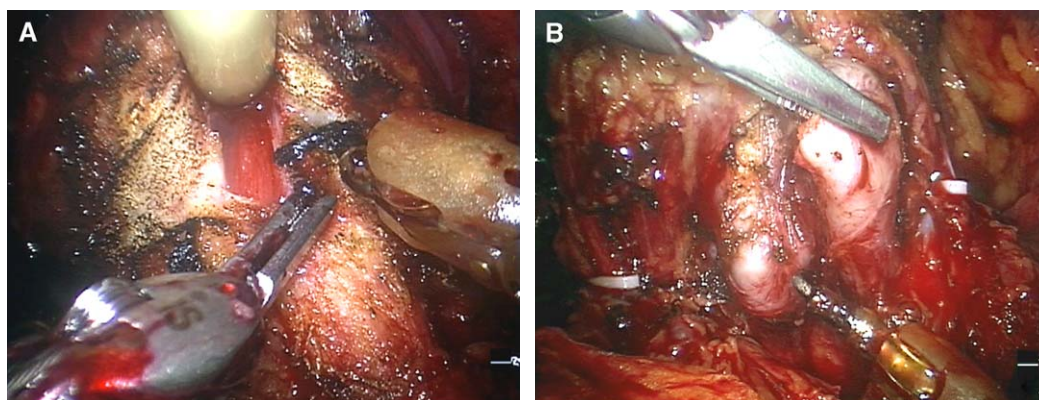


Fig. 7. (A) Division of anterior wall of bladder neck and Foley catheter can be seen through the window, which is retracted cranially. (B) Division of posterior bladder neck and Denonvillier's fascia leads to vas deferens (held with robotic grasper) and seminal vesicle.

prostatic fascia on the anterolateral surface of the prostate. These nerves may be physiologically relevant in erectile function [31–33]. To promote the earlier return of potency, the authors have attempted to preserve the accessory penile/cavernosal nerves in select individuals with low-volume, low-Gleason score disease. This part of the operation is done with articulated robotic scissors and bipolar forceps.

With the help of the robotic scissors, the layer of tissue containing the neurovascular bundle is dissected free, starting by incising the lateral pelvic fascia anteromedially and parallel to the neurovascular bundle between the prostatic venous plexus and the prostatic capsule. The posterolateral surface of the prostate is cleared by sharply dissecting away a layer of fascia, fat, nerves, and blood vessels from the base to the apex. The correct plane is between the prostatic venous plexus and the surface of the prostate. Once the correct plane is entered, most of the dissection occurs in a relatively avascular plane, and the neurovascular bundles can be teased away from the prostate easily (Fig. 8). The resulting neurovascular bundle is embraced in a veil of tissue, the so-called “veil of Aphrodite.”

*Division of the urethra, separation of specimen, and intraoperative apical biopsies*

The urethra is divided at the apex of the prostate, subsequent to the division of the puboprostatic ligaments, dorsal vein, and sphincter urethrae with the help of articulated robotic scissors (Fig. 9). The division of the posterior striated sphincter should be done carefully. Once

the urethra is transected, parietal margin biopsy specimens are obtained from the apex, base, and the area of the neurovascular bundles with the help of articulated scissors. The three-dimensional vision allows precise periurethral biopsies without sacrificing any length of urethra. In some cases, the authors also obtain biopsy specimens from the bladder base and bladder neck. These specimens are sent for frozen section; if any are positive (a rare occurrence), then additional biopsies are taken from the appropriate site. This helps lower positive margin rates at the apex [34].

*Bilateral pelvic lymphadenectomy*

This part of the dissection is done with the 0/30° lens. The retroperitoneal fat is cleared from the anterior surface of the external iliac vein. The external iliac vein is identified and dissected carefully along its inferior border. The obturator nerve is identified and serves as the posterior margin of dissection. Beginning at the pubic ramus, the lymph nodes and fatty tissues are cleaned out of the obturator fossa. Aberrant obturator vessels should be preserved, if possible, because they may help maintain potency. The packet of fibro-fatty and nodal tissue, which is normally one piece, is dissected toward the bifurcation of the external iliac vein. In patients with Gleason score 7 to 9 tumor, nodal tissue is removed posterior to the obturator nerve and vessels and anterior to the terminal branches of internal iliac artery, all the way to the surface of the pelvic musculature, which contains the internal iliac group of lymph nodes (Fig. 10).

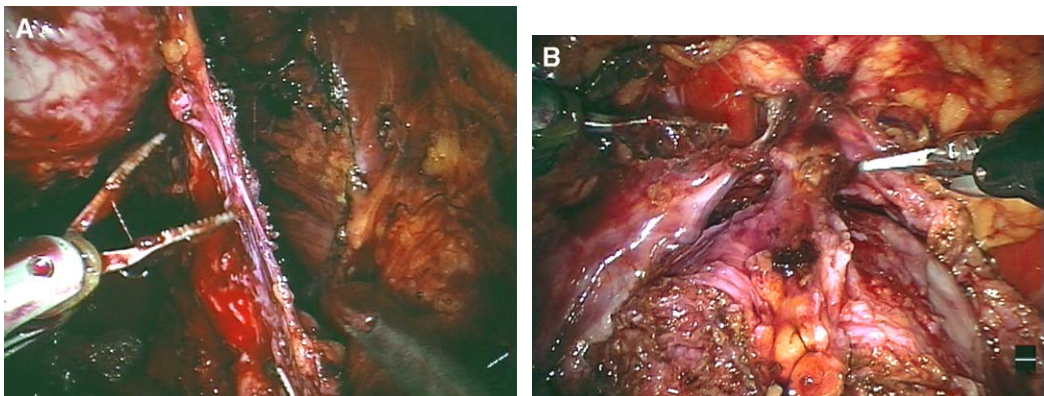


Fig. 8. (A) Preservation of right regular neurovascular bundle (pointed with the jaws of bipolar forcep), which was dissected off the posterolateral surface of the prostate. Prostate can be seen in lower and medial part. (B) Delineating dissected accessory nerves (veil of Aphrodite) on left side from antero-lateral surface of the prostate.

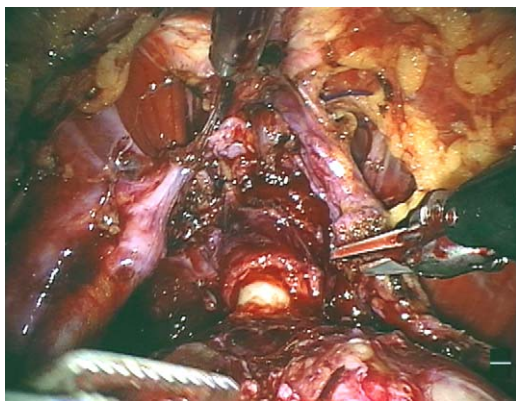


Fig. 9. Division of the urethra with the help of articulated scissors. Tip of Foley catheter can be seen emerging from the urethra. Recto-urethralis muscle is the last to be severed to detach the urethra from the prostate.

#### *Vesicourethral anastomosis*

The anastomosis is done using a slight modification of a technique published by van Velthoven and colleagues [34,35]. The tails of a 15- to 20-cm dyed and a 15- to 20-cm undyed 3-0 monocryl suture on a 17-mm round body (RB-1) needle (Ethicon), are tied to each other, making a single 30- to 40-cm suture with a bulky knot in the center and a needle at either end. The length of suture is guided by the width of the bladder neck.

The vesicourethral anastomosis is started by using the needle with the dyed end from the outside in at the 3- or 4-o'clock position of the



Fig. 10. Lymph node dissection of obturator, external iliac, and internal iliac group of lymph nodes. Arrow indicates obturator nerve.

bladder neck and inside-out from the urethra at the corresponding site. The authors apply a continuous suture in a clockwise fashion, taking three throws in the bladder and two in the urethra. After three throws, the suture is locked twice and cinched down. This brings the bladder neck to the urethra and forms the posterior plate. Because there is a wide plate of urethra and bladder with three stitches in either side, the stitches do not pull out in most instances.

The suture then is continued to the 9-o'clock position, where it is turned in toward the bladder (Connell) and run to the 12-o'clock position. By locking the sutures, the assistant needs not to "follow" the suture, which sometimes can be difficult in a patient with a narrow pelvis. The anastomosis is continued with the undyed end of the suture, passing it outside-in on the urethra at the 4-o'clock position, then inside-out on the bladder neck. After two throws on the urethra, it is locked on this side in similar fashion. The suture then is run counterclockwise until the end of the suture (dyed) is reached. The needles are cut off and the ends are tied together.

This approach has allowed the authors to complete the vesicourethral anastomosis with one intracorporeal knot (Figs. 11 and 12). This technique has been modified further, and the authors lock the sutures in between to make it segmental anastomosis because it helps in releasing tension and because assistance may not be needed, which is an arduous task in some patients as a result of narrow space. In some patients, additional interrupted sutures are applied to strengthen the anastomosis with RB-1 stitch (2-0 braided, polyglactin suture on a 17-mm tapered Ethicon needle).

The mean anastomotic time has been 14 minutes (range 8–20 minutes) over the last 600 cases, and the authors average 16 to 18 "bites" in the urethra and bladder neck. An indwelling 18F Foley catheter is inserted and leakage is checked with instillation of 200 mL of saline. A 14F Jackson-Pratt drain is left in to suck out any irrigation fluid that may have accumulated in the upper abdomen because of the Trendelenburg position.

#### **Development of extraperitoneal robotic prostatectomy technique**

The VIP is a hybrid technique that uses large peritoneal space for pneumo-insufflation,

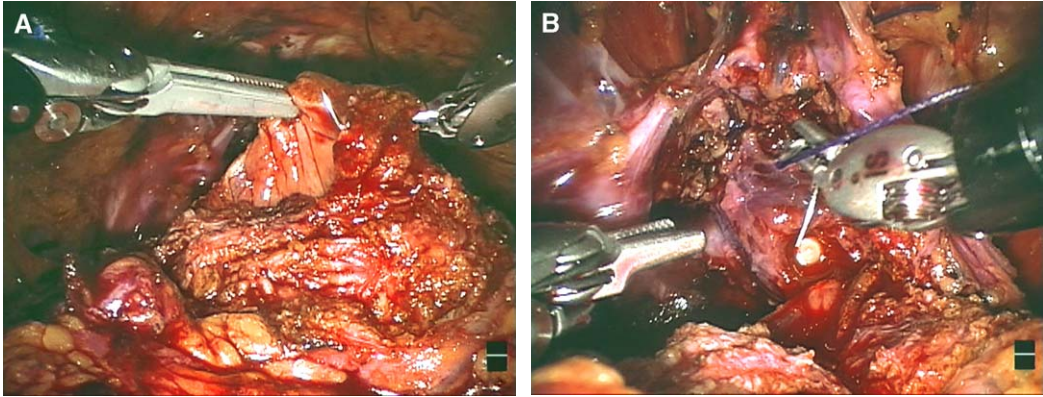


Fig. 11. (A) Vesico-urethral anastomosis in progress. One suture (length 25–36 cm, guided by the diameter of bladder neck) is prepared by tying dyed and undyed 3-0 monofilament suture on RB-1 needle. First throw of suture is being taken from the bladder neck at the 4-o'clock position. (B) After passing third throw of dyed suture through the bladder neck outside-in to the bladder, it is cinched down to approximate with urethral margin and suture is taken from urethral edge with dyed suture.

placement of the ports, and suction of smoke during the procedure. Except for the initial step of dropping the bladder, the rest of the procedure is performed in extraperitoneal space. The procedure also can be done with a completely extraperitoneal approach. The two approaches are similar, with the exception of port placement and creation of the working space.

#### *Positioning of the patient*

Patient positioning is similar as for VIP, but a less steep (15°) Trendelenburg position is used.

#### *Creation of extraperitoneal space and space of Retzius*

An infraumbilical incision is made 2.5 cm below the umbilicus, and deepened to the posterior rectus sheath. With the help of digital dissection, an extraperitoneal space is created for placement of the balloon, the subsequent inflation of which creates the wide extraperitoneal space. One also can create the space with the help of a laparoscope. A 12-mm camera port is placed through this site. Next, the two 8-mm robotic ports are placed under vision about 2 cm below the level of the camera port and lateral to the rectus muscle on either side equidistant from the camera port in a right angle

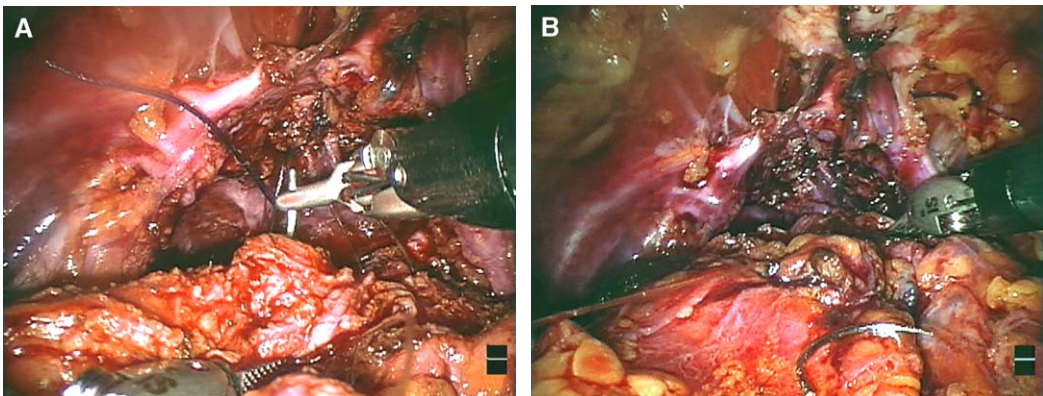


Fig. 12. (A) After clockwise anastomosis of bladder and urethra with dyed suture up to 11- or 12-o'clock position; anticlockwise anastomosis is started with undyed suture from 4-o'clock of the urethra outside-in and continued anteriorly. (B) Final completion of the anastomosis. Sutures (dyed and undyed) are ready to be tied together.

configuration. Two additional ports (5-mm port and 12-mm port) are placed for the assistant. This approach has been used successfully by other groups for LRP and in few cases with robotic assistance [26,36,37]. In the authors' experience of less than 50 cases, it has been somewhat more difficult to develop the space up to the bifurcation of the iliac artery, which is needed to perform a complete bilateral pelvic lymphadenectomy.

#### *Advantages*

The extraperitoneal robotic prostatectomy technique has the following advantages:

1. It mimics standard open surgery, and may make the anatomy more familiar.
2. It avoids potential risks or specific complications as a result of the transperitoneal approach, seen in 0.9% of the authors' patients.
3. In the inevitable anastomotic leak, the spillage of urine or blood is confined to the extraperitoneal space, and patients do not get urinary peritonitis.
4. The bowel does not flip in during the surgery.

#### *Disadvantages*

The extraperitoneal robotic prostatectomy technique also has the following disadvantages:

1. In the authors' hands, creation of extraperitoneal space adds about 30 minutes to the procedure. The average operative time was 120 minutes for VIP and 150 minutes for the extraperitoneal approach.
2. Avulsion of minor capillaries may mar the vision when the dissection is done bluntly.
3. The limited working space may collapse during suctioning of smoke. Sometimes the narrow space poses difficulty in carrying out extended bilateral pelvic lymphadenectomy.
4. There are specific anesthetic considerations; the increased partial carbon dioxide pressure may require increased minute ventilation, especially during the initial part of the procedure.
5. Some patients who have chronic obstructive pulmonary disease may not be suitable for this procedure.
6. Previous intra-abdominal surgery (laparotomy with infraumbilical or hypogastric incision) and previous bilateral hernia repair with or without mesh is a contraindication for this approach, unlike for VIP.

#### **Postoperative care**

Patients generally are discharged from the hospital within 24 hours. They return to the office 4 to 7 days after surgery for a cystogram and catheter removal. If there is no extravasation, the Foley catheter is removed. If extravasation is noted, then the catheter remains in place an additional 7 days and is removed without additional imaging.

#### **Results**

The authors have performed over 1100 cases of robotic radical prostatectomy. The operating time (Veress needle to closure) ranged from 70 to 160 minutes and the blood loss ranged from 50 to 250 mL. Approximately 20 to 40 minutes was spent in placing the ports, lysing any adhesions, retrieving the specimen, and closing the port sites. Thus, the actual robotic dissection (console) time is approximately 90 to 100 minutes. Pelvic lymphadenectomy took 18 minutes on average. No patient has required an intraoperative blood transfusion, no one donated autologous blood, and none received erythropoietin. Over 95% of patients are discharged within 24 hours, 3% stayed because of social reasons, and 2% stayed because of ileus.

#### **Comparison of conventional, laparoscopic, and robotic radical prostatectomy at the authors' center**

The authors also examined the outcomes of robotic radical prostatectomy and compared them to those of open and conventional LRP. The authors prospectively collected baseline demographic data on all patients undergoing surgery for prostate cancer over a 4-year period at their center. Urinary and sexual function were evaluated using standardized criteria preoperatively, and at 1, 3, 6, 12, and 18 months after the procedure. In addition, patients answered a mailed-in, validated questionnaire at these intervals. Operative and postoperative outcomes were compared using values for open radical prostatectomy as the reference standard. During the course of this study, the authors performed 100 open, 50 laparoscopic, and 565 robot-assisted radical prostatectomies. As the study progressed, patient preferences changed, with over 80% of patients currently choosing robotic over open surgery.

Tables 3 lists operative, functional, and oncologic outcomes for the patients. Robotic and

Table 3

Odds ratio for important outcomes for laparoscopic, robotic, and radical retropubic prostatectomy performed at the Vattikuti Urology Institute

Variables	Open radical prostatectomy (reference values)	Laparoscopic radical prostatectomy (odds ratio)	Robotic prostatectomy (odds ratio)
Operating room time	163 min	1.51 <sup>a</sup>	0.91 <sup>b</sup>
Estimated blood loss	910 mL	0.42 <sup>a</sup>	0.10 <sup>a</sup>
Positive margins	23%	1	1
Complications	15%	0.67 <sup>a</sup>	0.33 <sup>a,b</sup>
Catheterization time	15.8 d	0.50 <sup>a</sup>	0.44 <sup>a</sup>
Hospital stay > 24 hr	100%	0.35 <sup>a</sup>	0.07 <sup>a,b</sup>
Postoperative pain score (0–10)	7	0.45 <sup>a</sup>	0.45 <sup>a</sup>
Median time to continence	160 d	1	0.28 <sup>a,b</sup>
Median time to erection	440 d	NA <sup>c</sup>	0.4 <sup>a</sup>
Median time to intercourse	> 700 d	NA <sup>c</sup>	0.5 <sup>a</sup>
Detectable prostate specific antigen	15%	1	0.5

<sup>a</sup>  $P < .05$  compared with radical retropubic prostatectomy.

<sup>b</sup>  $P < .05$  compared with laparoscopic radical prostatectomy.

<sup>c</sup> Most patients undergoing laparoscopic radical prostatectomy were not sexually active at baseline.

Abbreviation: NA, not available.

The reference values were those from conventional radical prostatectomy; odds ratio was the ratio of the observed to the reference value.

Data from Refs. [24,27].

laparoscopic radical prostatectomy resulted in less pain and intraoperative blood loss than open surgery. The odds ratios for operative times, blood loss, postoperative pain, prostate-specific antigen recurrence, and the median times for return of continence and sexual function were lowest for VIP. Robotic technology also offered the ability to remove additional tissue from critical locations and lowered the positive margin rate. LRP occupied an intermediate position with lower odds ratios than conventional surgery for all parameters except operative time and margin positivity. These results compare favorably with those from published series (Tables 4) of laparoscopic or open radical prostatectomy.

### Complications

There was no operative mortality and no patient was converted to open surgery. No patient received an intraoperative transfusion. There were 21 unscheduled postoperative visits for transient urinary retention after early catheter removal (15), dysuria (four) or hematuria (two). Postoperative complications were defined according to the classification of Clavien. Grade-1 postoperative

complications were defined as deviations from ideal occurring within 30 days of surgery. There were 10 Grade-1 complications: four patients developed postoperative anemias as a result of bleeding from the port site (two) or pelvic hematomas (two), five developed ileus lasting more than 24 hours, and one had a stitch abscess. There were four grade-2 complications, defined as potentially life-threatening complications without permanent sequelae: one deep vein thrombosis, two bowel injuries during lysis of adhesions in patients with history of peritonitis and extensive lower abdominal surgery, and one bronchial edema secondary to difficult intubation.

Patients who did not have an International Prostate Symptom Score less than 5 at 6 months were cystoscoped to rule out anastomotic stricture. At 12 months, nine patients developed a bladder-neck contracture and one developed meatal stenosis. There were two rectal injuries that were identified intraoperatively and closed uneventfully. Two patients developed an incisional hernia at the site of specimen retrieval. One patient has developed a recurrence of an umbilical hernia and one patient presented with clot retention 4 weeks after catheter removal.

Table 4  
Operative parameters for conventional, laparoscopic, and robotic radical prostatectomy (VIP)

Technique	Operating time (min)	Estimated blood loss (mL)	Duration of catheterization(d)	Complication rates (%)	Positive margins (%)
<b>RRP</b>					
Lepor	131	820	7–10	6.6	17
Catalona	217	1395	7–14	10	21
<b>LRP</b>					
Montsouris	217	345	6.6	13.3	15
Rassweiler	278	1230	8	31	17
Abbou	271	NA	9	11.66	18.1
Turk	214	177	10	14	16–39
<b>VIP</b>					
Menon, Tewari	160	153	7	5	6

Abbreviations: NA, not available, LRP, laparoscopic radical prostatectomy; RRP, radical retropubic prostatectomy. Data from Refs. [6,7,14–16,24,27,38–47].

### Functional results

Total continence, defined as using no pad, was achieved in 96% of patients at a follow-up of 6 months, at a median time of 42 days [13,23,24]. Based on validated third-party questionnaires (Expanded Prostate Cancer Index Composite), 82% of preoperatively potent patients younger than 60 years of age had a return of some sexual activity, and 64% had had sexual intercourse at a follow-up of 6 months. Of patients over 60 years of age, 75% had had some sexual activity and 38% had had sexual intercourse [23].

### Comments

Laparoscopic technique provides four degrees of freedom of movement, compared with robotic surgery, which provides six degrees of freedom. In addition, current laparoscopic displays do not provide three-dimensional orientation and lack tactile feedback. The instruments are not ergonomically suitable for difficult operations such as an LRP [48]. In the earlier experience of LRP, the greatest time required was in creating the urethrovesical anastomosis, which took twice as long as the time for the actual removal of the prostate [49].

Many of these disadvantages can be overcome with robotic technology. The da Vinci surgical system is a master-slave robotic system. The assistance of this robot allows an open surgeon to perform complex laparoscopic procedures. The features of the robot that make it superior include: three-dimensional visualization with 10× magnification, wristed instrumentation (intuitive and finger-controlled movements), ergonomic manipulation of the robotic instruments without fatigue, and a comfortable seat for the surgeon

[50]. The authors believe the superior view provided by the da Vinci system allows successful identification of the correct tissue planes. In addition, the improved coordination provided by the system allows one to perform a more anatomic dissection. The vesicourethral anastomosis could be performed with robotic assistance in 20 to 30 minutes in the authors' earlier experience; this time has dropped to 10 to 20 minutes [34]. The other significant advantage of the VIP technique is the minimal blood loss, requiring no transfusion [24,28]. Several reports from different centers in the world have repeated the success achieved by the authors (Tables 5).

Minimally invasive surgical techniques have received positive attention from surgeons and patients. This increased attention is secondary to the many benefits, including the potential for decreased postoperative discomfort, minimal disfigurement, and a quicker recovery compared to conventional surgery. Although cost has been a major concern, rapid recuperation has provided the impetus to continue to offer these procedures for patients. Treating prostate cancer effectively, which can be defined on the basis of the complete removal of the prostate, excision of nodes, and positive margin rates, is still a concern to some.

In this aspect of surgery, robotic (VIP) and LRP are fairly well established. When evaluating the outcomes of continence, the VIP technique has better outcomes than open surgery because the time to continence is shorter. Patients are also likely to regain potency faster than with open surgery because neurovascular bundles are protected under vision, although long-term data evaluation is necessary [28,33]. The time for vesicourethral anastomosis has been decreased to less than 15 minutes

Table 5

Experience of robotic radical prostatectomy from different centers in the world

References	Patients (No.)	SX access	Operative time (min)	Blood loss (mL)	Hospital stay (d)	Catherization	% Positive margin (No.)
Binder and Kramer	10	TP	450 (535–660)	Not recorded	Not recorded	18 (5–23)	30 (3)
Pasticier and colleagues	5	TP	222 (150–381)	800 (700–1600)	6.5 (4–7)	6.5 (5–9)	20 (1)
Rassweiler and colleagues	6	TP	315 (242–480)	Not recorded	Not recorded	7.3 (5–14)	0
Samadi and colleagues	11	TP	300 (200–420)	900 (400–1600)	Not recorded	(2–5)	27 (3)
Menon and colleagues	40	TP	274	256	Not recorded	Not recorded	18 (7)
Menon M	100	TP	140	<100	1.2	7	5
Bentas W	40	TP	8.3 h	570			
Ahlering and colleagues	45	TP	179–382	134 (50–350)	1, 2, 3, and 7	7	35.5 (16)
Menon and colleagues	200	TP	160	153 (25–750)	1.2	7 (1–18)	6
Wolfram and colleagues	118	EP-7,TP-R					
Gettman and colleagues	4	EP	274 (124–360)	1013 (550–1500)	5.3 (3–9)	2.7 (2–3)	25 (1)
Ahlering and colleagues	60	TP	231 (160–340)	103 (25–400)	25.9 h	7	16.7 (10)

*Abbreviations:* EP, extraperitoneal; SX, surgical; TP, transperitoneal.

in 90% of VIP cases. This is a result of the excellent anatomic dissection, visualization, precision, accuracy, and the dexterity of the robot with the scaling and filtering of hand movements. With the VIP approach, anastomotic leaks are usually extraperitoneal and remain confined to this space. This eliminates morbidity of urinary leakage into the peritoneal cavity.

### Summary

Advances in surgical techniques, technology, and surgeons' skills have allowed robot-assisted radical prostatectomy to be an option in the management of organ-confined prostate cancer. The goals of the VIP technique are to cure cancer, preserve urinary continence, preserve potency, and decrease morbidity, along with the benefits of a minimally invasive surgery and excellent cosmesis. VIP is nearly equal to traditional retropubic prostatectomy, with certain outstanding advantages.

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## Robotic radical cystectomy and urinary diversion in the management of bladder cancer

Ashok K. Hemal, MD, MCh, FACS<sup>a,\*</sup>, Hassan Abol-Enein, MD<sup>b</sup>,  
Ashutosh Tewari, MD<sup>a</sup>, Alok Shrivastava, MD<sup>a</sup>,  
Ahmed M. Shoma, MD<sup>b</sup>, Mohammed A. Ghoneim, MD<sup>b</sup>,  
Mani Menon, MD, FACS<sup>a,c</sup>

<sup>a</sup>Vattikuti Urology Institute, Henry Ford Hospital, 2799 West Grand Boulevard, K-9, Detroit, MI 48202-2689, USA

<sup>b</sup>Urology and Nephrology Center, Mansoura University, Mansoura, Egypt

<sup>c</sup>Department of Urology, Case Western Reserve University, 11000 Euclid Avenue, Cleveland, OH 44106-4931, USA

Bladder cancer, the fourth most common cancer in men and the eighth most common cancer in women in the United States, is prevalent worldwide [1]. Superficial bladder tumors are treated effectively with transurethral resection with or without intravesical chemotherapy [2]. For muscle-invasive, organ-confined bladder cancer, however, radical cystectomy is the most effective treatment. Marshall and Whitmore [3] gave the first detailed operative description of radical cystoprostatectomy and pelvic lymphadenectomy in 1949.

The advent of nerve-sparing cystectomy and orthotopic bladder substitution has provided many patients with good local and regional control, as well as good quality of life. The goal of radical cystectomy in men is to remove the bladder with its perivesical fascia, peritoneal covering, the prostate, and seminal vesicles together with the endopelvic lymph nodes. In women, the bladder, uterus, adnexa, and upper half of the vagina with pelvic cellular tissue also are removed. Preservation of the urethra protected by an intact pelvic floor is feasible if orthotopic substitution is indicated. In open radical surgery, wide direct exposure requires

a long vertical abdominal incision from the symphysis pubis inferiorly to halfway between the umbilicus and xiphoid process. Radical cystectomy is a formidable surgical procedure, associated with significant complications even in expert hands [4].

Laparoscopic surgery is becoming more popular in urologic practice and has expanded from ablative to reconstructive surgery. There are selective reports of laparoscopic radical cystectomy alone, with extracorporeal diversion [5–9], with completely intracorporeal ileal conduit [10], or with different forms of continent urinary diversion [11–13]. These laparoscopic procedures are technically challenging, however, and generally are significantly longer procedures than their open counterparts. There also may be complications, especially during the initial period of experience [14,15].

The advantages of robotic assistance have been used efficiently in advanced uro-oncologic surgery, such as robot-assisted radical prostatectomy and robot-assisted radical cystoprostatectomy (RRCP) for patients who have muscle-invasive bladder cancer [16,17]. RRCP allows precise and rapid removal of the bladder with minimal blood loss, which translates to minimal morbidity with equivalent success to open surgery. This article reviews the published literature and details the authors' current technique of robotic radical cystectomy and urinary diversion.

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\* Corresponding author.

E-mail addresses: [akhemal@hotmail.com](mailto:akhemal@hotmail.com)  
[ahemall@hfh.org](mailto:ahemall@hfh.org) (A.K. Hemal).

## Surgical procedure

1. RRCP in males and robot-assisted radical cystectomy (RRC) in women
2. Urinary diversion
3. Urethro-neobladder anastomosis

### *Robot-assisted radical cystoprostatectomy and robot-assisted radical cystectomy*

#### *Preparation and positioning of patient*

Bowel preparation with antibiotic coverage is initiated 1 day before the procedure. On the morning of surgery, a broad-spectrum antibiotic and subcutaneous heparin, 5000 units, are administered. Bilateral leg compression stockings are applied. After induction of anesthesia, sufficient padding around the shoulders, elbows, sacrum, and crossed thoracic wraps is applied over the foam padding. The arms are tucked in by the side of abdomen. The patient is placed in an extended lithotomy position with a 45° Trendelenberg tilt (to allow the bowels to fall back and open the pelvic cavity). The table is lowered and the robot is installed between the separated legs. A Mayo stand is placed near the head end covering the face, which is used for placing the instruments during the surgery; in addition, it protects the patient's face and prevents inadvertent movement of the endotracheal tube. A nasogastric tube and a urethral catheter are inserted.

#### *Equipment and instruments*

Standard robotic instruments with few laproscopic instruments are required, in addition to different suture materials for different steps of surgery. Most of the dissection is performed with two instruments: the da Vinci long-tip forceps and the cautery hook. Alternatively, the bipolar-coagulating forceps and the articulate scissors are used; the authors use these instruments particularly for the nerve-sparing part of the surgery, urethral dissection, and extended bilateral pelvic lymphadenectomy. The da Vinci long-tip forceps and robotic needle driver are used for urethra-neobladder anastomosis. Then the patient-side assistant uses the grasping forceps and suction cannula for suction, irrigation, retraction, countertraction, and exposure.

#### *Placement of ports*

Pneumoperitoneum is created using a Veress needle (Ethicon Endo-Surgery, Albuquerque, New Mexico) at the proposed site of the primary port in the umbilical region (superior). After

initial insufflation, a 12-mm primary port is inserted and the entire peritoneal cavity is inspected with a 30° laparoscope. The two 8-mm robotic ports are introduced lateral to the rectus muscle and 2 to 3 cm below the level of umbilicus on either side, and, in patients where ileal conduit is contemplated, the right robotic port is placed at the proposed site of the stoma. These two 8-mm robotic working ports should be placed 7 to 10 cm away from the camera port to avoid collision of the robotic arms and to maximize movement. A second 12-mm port is placed in the right iliac fossa 2 to 3 cm above the iliac crest in the midaxillary line. The fifth port (5-mm) is placed between the robotic and camera ports on the right or left side, as preferred by the assistant. If this port is placed at the level of umbilicus or higher, then a long-tip suction cannula should be used. The sixth (optional) 5-mm port may be placed on the left side between the primary camera port and the left robotic port, or in the left iliac fossa, as needed for retraction. Fig. 1 shows the placement of ports in the transperitoneal approach. All secondary ports are inserted under laparoscopic vision using an upward-looking 30° laparoscope.

#### *Posterior dissection (incision at the cul-de sac, dissection of the ureters, identification of seminal vesicles, and incision of Denonvillier's fascia to develop rectoprostatic plane)*

In the first five cases, the authors started by performing a bilateral extended pelvic



Fig. 1. Placement of ports for robotic radical cystectomy: 12-mm camera port (arrow near umbilicus), two metal ports (arrowheads) for robotic arms, and three other ports (arrows) for assistance with laparoscopic instruments.

lymphadenectomy (Fig. 2), ligating the superior and inferior vesical pedicles as the operation proceeded. The authors found, however, that developing and transecting the rectovesical pedicles was difficult, particularly in obese patients, patients with a narrow pelvis, those with bulky tumors, or those who had pelvic inflammation secondary to Bilharziasis. Because essentially all patients had one or more of these characteristics, the authors modified the technique, performing the posterior dissection initially. The angled lenses combined with the wristed instrumentation help develop the rectovesical plane. This plane of dissection also provides opportunity to begin preserving the neurovascular bundles, if indicated, before the anterior and latter bladder dissection is performed.

In the authors' practice, the posterior dissection is done with the 30° lens, looking downward. An inverted U-shaped incision is made in the peritoneum of the cul-de sac. In many patients, the course of the lower ureters can be seen as a peritoneal fold that extends from the iliac bifurcation to the posterior bladder wall. When this is seen, the vertical limbs of the U follow this course, extending to a point approximately 2 to 3 cm proximal to the bifurcation of the common iliac artery. The patient-side laparoscopic assistant provides equal countertraction on the transected peritoneal folds and the surgeon dissects all fatty and fibrovascular tissue off the posterior

peritoneal fold. The posterior layer of Denonvillier's fascia is incised in the midline and the plane between the rectum and the bladder is developed as far inferiorly as is easily possible. The planes are extended laterally, such that a broad dissection front is maintained.

This leads to the ureter, which lies on the undersurface of the posterior peritoneum. The ureters are dissected to the bifurcation of the iliac vessels proximally, and the ureterovesical junction distally. In men, the ureterovesical junction can be identified immediately inferior to the crossing vas deferens on the posterior bladder surface. It is important not to dissect the vas deferens off the posterior surface of bladder to maintain this anatomic landmark. The inferior vesicle pedicle usually is encountered during this phase of the dissection (Fig. 3) and must be secured and divided. The ureter then is clipped and transected, and the margins sent for frozen section. The seminal vesicles are identified immediately medial to the lower end of the ureters. These are dissected down to their base. To preserve the nerves, which are located close to the tips of the seminal vesicles, this dissection is performed immediately adjacent to the walls of the seminal vesicle, between the seminal vesicle and the posterior layer of Denonvillier's fascia (which can be seen clearly if dissection has been in the proper planes). The rectoprostatic plane is developed as feasible by dividing Denonvillier's fascia.

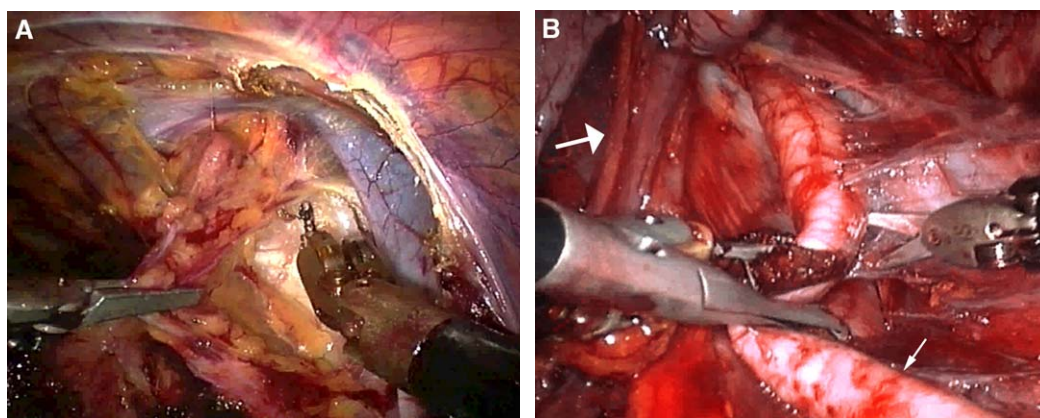


Fig. 2. (A) Dissection of lymph node package from obturator fossa. Also seen are the external iliac vein and the circumflex iliac vein. (B) The lymphatic package is dissected from underneath the iliac vessels. Thick arrow indicates the obturator nerve, and obturator vessels are seen; thin arrow indicates the external iliac artery. (From Menon M, Hemal AK, Tewari A, Shrivastava A, Shoma AM, El-Tabey NA, et al. Nerve-sparing robot-assisted radical cystoprostatectomy and urinary diversion. *BJU Int* 2003;92(3):232–6; with permission.)

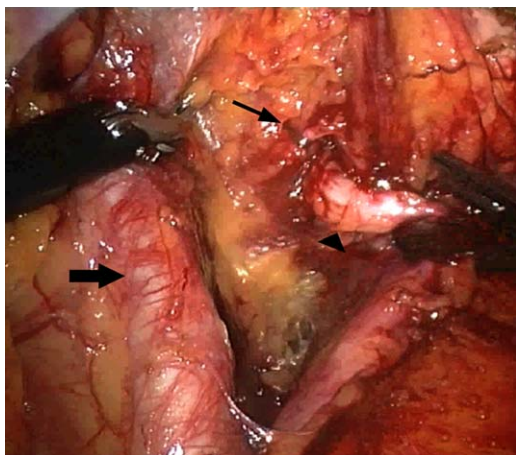


Fig. 3. View after posterior dissection, with a clip over inferior vesical artery (*thin arrow*), uretero-vesical junction (*arrowhead*), and iliac artery (*thick arrow*) through posterior incision of inferior fold of peritoneum in the retrovesical area (cul de sac). (From Menon M, Hemal AK, Tewari A, Shrivastava A, Shoma AM, El-Tabey NA, et al. Nerve-sparing robot-assisted radical cystoprostatectomy and urinary diversion. *BJU Int* 2003;92(3):232–6; with permission.)

*Mobilization of the bladder, control of the bladder pedicles, endopelvic fascia incision, and control of dorsal vein complex*

The bladder is dissected off the anterior abdominal wall by incising the anterior peritoneum. This incision is lateral to the medial umbilical ligament (obliterated umbilical arteries) on either side and inferiorly transects the vas deferens. The incision then curves medially under the rectus abdominis, transecting the medial umbilical ligaments and the urachus. Thus, prevesical space is entered and it is dissected further down to expose the space of Retzius. The superior vesical pedicle is clipped and transected at its origin (Fig. 4). The anterior trunk of the internal iliac artery continues as the inferior vesical artery, which gives off vesical branches (secured now if not done during the earlier posterior dissection) and terminates as the prostatic artery. This vessel is dissected until it bifurcates into the urethral artery and capsular artery. The urethral artery is clipped and transected, but the capsular artery, which forms the vascular part of the neurovascular bundle, is preserved. Identification of the capsular artery enables the subsequent preservation of the neurovascular bundles. The endopelvic fascia is opened lateral to the prostate and the prostate-urethral junction is identified. The dorsal vein complex is



Fig. 4. Dissected superior vesicle artery (*arrow*). (From Menon M, Hemal AK, Tewari A, Shrivastava A, Shoma AM, El-Tabey NA, et al. Nerve-sparing robot-assisted radical cystoprostatectomy and urinary diversion. *BJU Int* 2003;92(3):232–6; with permission.)

secured using a suture of 0 vicryl on a CT1 needle [18].

*Preservation of the neurovascular bundles*

The seminal vesicles are used as an operative landmark to avoid injury to neurovascular bundles and follow the principles described earlier. Dissection is performed in the plane between the posterior surface of the seminal vesicles and the posterior layer of Denonvillier's fascia. Monopolar coagulation is avoided, and the da Vinci articulated scissors and bipolar forceps are used for this step. Dissection should be meticulous and stay close to the prostatic surface, reflecting the lateral pelvic fascia off the prostate. Such precision is possible because the vesical and prostatic pedicles have been controlled at this point. The neurovascular bundle then is reflected off laterally, leaving a layer of Denonvillier's fascia on the surface of the rectum.

*Division of urethra*

The urethra is divided at the apex of prostate with the help of articulated robotic scissor (Fig. 5). Obtaining the maximum length of urethra is attempted, which would help subsequently in anastomosis with neo-bladder. To divide the anterior wall of the urethra, the puboprostatic ligaments, ligated deep dorsal vein complex, and striated urethral sphincter are divided; then, the posterior wall of urethra is divided and it is freed from the rectourethralis muscle and Denonvillier's fascia, freeing the specimen. The specimen is entrapped in

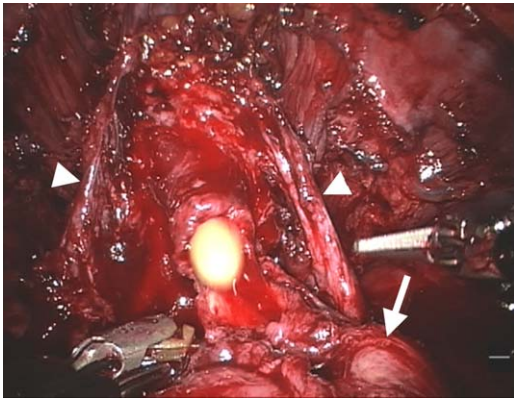


Fig. 5. Divided urethra, apex of the prostate (arrow), and bilateral preserved neurovascular bundles (arrowhead).

an Endocatch II bag (US Surgical, Norwalk, Connecticut).

#### *Technique of bilateral extended pelvic lymphadenectomy*

The bilateral extended pelvic lymphadenectomy is performed after radical cystectomy. The anatomic limit of extended lymphadenectomy is commensurate with standard open surgery (see Fig. 2). The dissection is performed with robotic bipolar forceps in the left hand and robotic articulating scissors in the right hand. The peritoneum is incised in the line of the external iliac artery from the apex of the U proximally to the inguinal ligament distally. A standard pelvic lymphadenectomy is done using the 0°/30° degree downward lens. The 30° downward lens is essential for the proximal dissection over the common iliac artery. The limit of dissection is the Cloquet lymph node distally, genitofemoral nerve laterally, and the bifurcation of the common iliac artery proximally. The loose fibroareolar tissue is swept off the psoas muscle medially; then the external iliac artery, external iliac vein, and obturator nerve are skeletonized, extending the proximal limit dissection up to the bifurcation of the common iliac artery.

In some cases, obturator vessels were excised in keeping with the Mansoura group philosophy of getting the maximum number of lymph nodes, although its benefits are not proved. While dissecting distally, one has to be cautious of the accessory obturator vessel and the anomalous vein, which often are hidden behind the lymph node. Similarly, caution is advised when

skeletonizing the external iliac vein because it appears flat as a result of pneumoperitoneum. The nodal tissue seems to form three natural packages: (1) one attached to the bladder wall; (2) one lateral to this; and (3) another packet of nodes, the internal iliac group, posterior to the obturator vessels and anterior to branches of the internal iliac vessels, which also is recovered with continuing dissection posterior to the obturator nerve and vessels to the levator ani and iliacus muscle. Lymphadenectomy requires caution because the tissue contains multiple small blood vessels that have to be coagulated meticulously. Otherwise, they retract into the tissues and begin hemodynamically insignificant oozing that impairs visibility and may obscure the detection of precise tissue planes. After completion of lymphadenectomy, lymph nodes are secured in an Endocatch I bag (US Surgical).

#### *Extraction of the specimen*

A 5- to 7-cm midline vertical incision is placed midway between the umbilicus and pubic symphysis or near the umbilicus to retrieve the specimen (Fig. 6). Because the authors perform urethra-neobladder anastomosis robotically, a long incision extending to the hypogastrium, essential during open surgery, is not needed.



Fig. 6. Delivery of specimen through the abdominal incision, which is entrapped in a laparoscopic Endocatch II bag (US Surgical). (From Menon M, Hemal AK, Tewari A, Shrivastava A, Shoma AM, El-Tabey NA, et al. Nerve-sparing robot-assisted radical cystoprostatectomy and urinary diversion. *BJU Int* 2003;92(3): 232–6; with permission.)

### Urinary diversion

The bowel is exteriorized through the 4- to 6-cm midline incision used for extraction of the specimen. The transected distal ends of the ureters are identified and mobilized proximally, if necessary. The left ureter is transposed from left to right through an opening in the descending sigmoid mesocolon. The distal ends of the transected ureters are fixed with stay sutures to avoid malrotation or kinking. The ureters are brought out of the incision.

### Ileal loop conduit

A 15- to 20-cm long segment of the terminal ileum is brought out of the surgical wound. Attention is paid to preserve the distal 20 cm of the ileum near the ileocecal junction, which is important for vitamin B-12 absorption. It is also necessary to pay attention to the mesentery and avoid twisting or rotation. Ileum-to-ileum anastomosis is performed at the seromuscular level using interrupted 4/0 polydioxanone (PDS) suture. The isolated ileal segment is flushed to clean out fecal content. Ureteroileal anastomosis is performed in standard fashion with Bricker principles. The authors prefer an end-to-side ureteroileal anastomosis, but in patients with dilated ureters, Wallace technique is adopted. The ureteral stents are brought out through the distal end of the loop. The ileal loop with the attached ureters is repositioned into the abdomen. The ileal conduit is fixed near the sacral promontory and also to the abdominal wall to avoid twisting or kinking. Finally, an everted skin stoma is performed in the standard fashion. The ureteral stents are left in place for 7 to 10 days.

### Orthotopic ileal pouch

*Classic ileal W neobladder with serous lined extramural tunnel ureteral implantation.* A 40-cm ileal segment is isolated with a wide mesenteric supply. Ileal-ileal anastomosis is performed as discussed previously. The isolated segment then is arranged in a “W” configuration (Fig. 7). The adjacent edges of the W ileal segment are approximated for 3 cm using 4/0 continuous silk suture, which will be used as a serous-lined trough for subsequent ureteric reimplantation. The ileum then is incised using a diathermy needle starting from the proximal limbs of the W, and the width of each serous-lined trough is adjusted according to the diameter of ipsilateral ureter. The incision is continued throughout the ileal segment. The two ileal medial flaps are approximated using 4/0 PDS

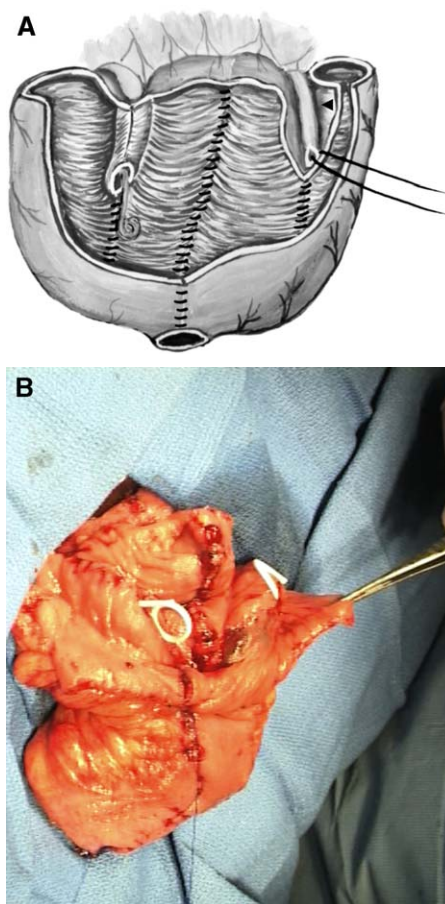


Fig. 7. (A,B) A 40-cm distal ileum segment in “W” configuration outside the 6- to 7-cm wound with the two respective ureters. The ureters are embedded in the serous-lined troughs. Mucosa-to-mucosa anastomosis is performed leaving a double J stent.

continuous suture [18]. The suture line is continued from within until 5 to 7 cm distant from the cut ends of the bowel segment. The ileal flaps also are approximated distal to the end of the serous-lined trough using 4/0 PDS continuous suture.

In this way, the tubular ileal segment is converted to a pouch plate with two serous-lined troughs. The most dependent part of the pouch plate is pushed down to ensure the most dependent part of the reservoir (the bladder neck of the neo-bladder). An opening then is created by cutting a few stitches from the continuous suture line, and the end of the opening is secured by a single stitch on either side. The ileal mucosa is everted using 4/0 PDS suture to avoid urethra-ileal anastomotic stenosis. One J stent is passed

through the ureter to avoid unrecognized kinking or twisting. Each spatulated ureter is laid in its corresponding trough and mucosa-to-mucosa anastomosis is performed. The ileal flaps of the troughs are approximated using 5/0 PDS interrupted suture. The neo-bladder (pouch) then is closed by approximation lateral to most ileal plates (Fig. 8). A marking stitch is left in place at the 12-o'clock position for identification of the neo-bladder neck during urethra-neobladder anastomosis with robotic assistance.

**Modification.** In cases of massively dilated or short ureters as a result of tumor or dysplasia, the classic serous-lined technique may not be feasible. Adequate length of the ureters is essential for a tension-free anastomosis. The modification uses a separate tapered ileal segment embedded in a serous-lined tunnel to serve as an antireflux mechanism for both ureters. A 6- to 8-cm long ileal segment is isolated (to serve as an antireflux inlet) in addition to the “W” segment of ileum. The pouch is fashioned leaving the left serous-lined trough open. The isolated ileal segment is tapered over a 20F catheter at its distal two thirds [19]. Four mesenteric windows are created between the mesenteric vascular arcades of the

tapered segment. Then, the tapered ileal segment is passed into the serous-lined trough while the blood supply is well preserved (Fig. 9). Two internal stents are passed through this segment into the pouch prior to closing. Both ureters are evaluated and traced proximally, ensuring no twisting and kinking. End-to-side uretero-ileal anastomosis is performed. Wallace end-to-end technique is used when the ureters are dilated.

In most cases, orthotopic neobladder (detubularized ileal W-bladder) is performed unless there is specific contraindication.

#### *Urethra-neobladder anastomosis*

A 22F silicon soft urethral catheter is inserted and its tip is guided from the urethral stump and passed into the pouch cavity. The catheter balloon is inflated by 20 mL saline. The pouch is filled with saline to ensure a watertight closure. The pouch then is introduced back into the abdominal cavity and directed down toward the pelvis with traction on the urethral catheter. The ureters are inspected in their final position, ensuring no tension. The abdominal incision is closed and the robot is reinstalled for anastomosis of the neo-bladder with the urethra (Fig. 10). The table is tilted to

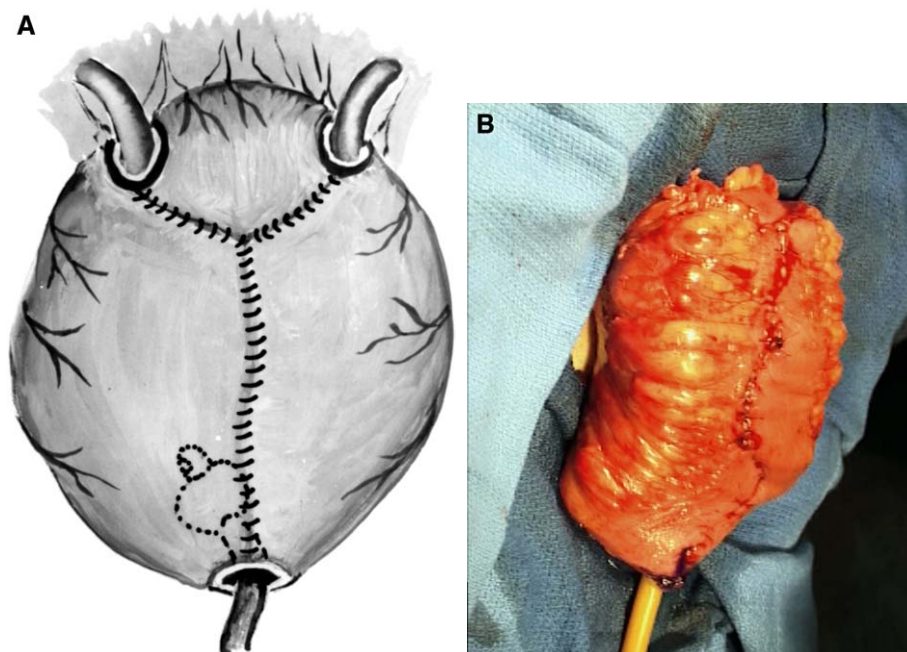


Fig. 8. (A) A lined diagram of the closed pouch after uretero-ileal anastomosis. Urethral catheter is seen. (B) Extracorporeally created neobladder through abdominal incision used for delivery of specimen.

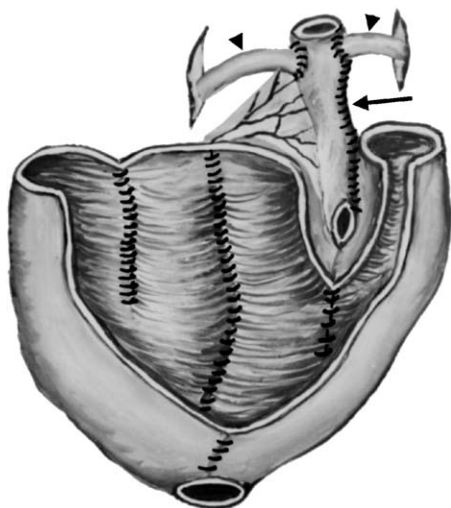


Fig. 9. Variant of “W” orthotopic neobladder in which a 6- to 8-cm long ileal segment is isolated (to serve as an antireflux inlet) in addition to the “W” segment of ileum. The ureters (arrowheads) are anastomosed to a tapered ileal segment (arrow) embedded in a serous-lined tunnel.

15° Trendelenburg position to avoid traction on anastomosis. A 0° lens without scaling is used at this step of the operation.

One suture is prepared by tying the tails of two 3-0 poliglecaprone 25 (monofilament) sutures (one dyed and one undyed for ease of identification during anastomosis) on an RB-1 needle (Ethicon Endo-Surgery) to perform a running anastomosis using the previously described Menon, van Veltoven, Ahlering, Clayman (MVAC) suture and principles of anastomosis with robot [20]. A previously placed tag suture at the 12-o’clock position helps align the neobladder while performing urethra-neobladder anastomosis (see Fig. 10). In some patients, additional interrupted sutures are applied to strengthen the anastomosis with RB-1 stitch (2-0 braided, polyglactin suture on a 17-mm tapered needle (Ethicon Endo-Surgery).

#### Postoperative care

The patient is monitored as per the regular protocol. Fluids and electrolytes are monitored. The nasogastric tube is left in place for 1 day. Oral liquid diet is allowed after bowel sounds return. Parenteral broad-spectrum antibiotics are given postoperatively. Flushing and irrigation of the neobladder is started on postoperative day 3 using saline once or twice a day to clear the mucus.

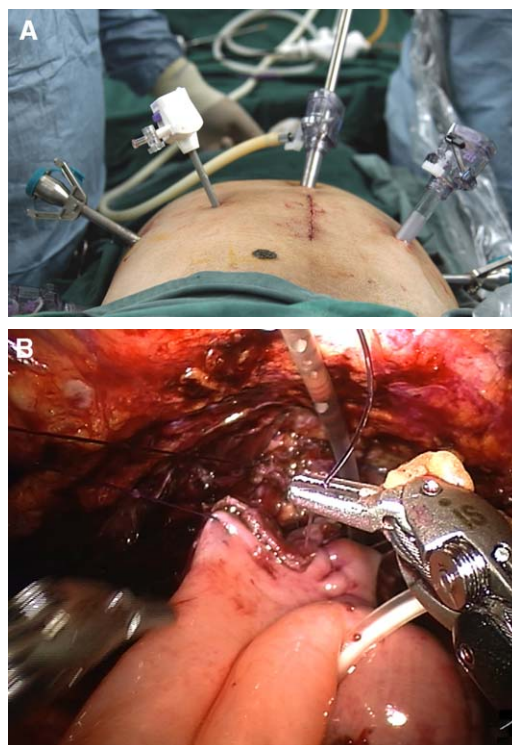


Fig. 10. (A) View after redocking the robot showing closed incision on the abdomen and spatial placement of the sixth port to complete the anastomosis of neobladder to the urethra. (B) Urethra-neobladder anastomosis in progress with robotic assistance. (From Menon M, Hemal AK, Tewari A, Shrivastava A, Shoma AM, El-Tabey NA, et al. Nerve-sparing robot-assisted radical cystoprostatectomy and urinary diversion. *BJU Int* 2003;92(3):232–6; with permission.)

Estimation of creatinine from the drainage fluid may be required if urine leak is suspected. The drain is removed after the drainage has minimized per the standard protocol. The patient is discharged 3 to 5 days postoperatively. Oral fluorquinolones are administered for 10 days. Cystogram is performed at 10–14 days postoperatively, before removal of the urethral catheter.

#### Results

RRCP was performed in 21 men and RRC was performed in three women. In men, the technique of nerve-sparing RRCP was used unless there were specific issues. In women, the operation was performed with the conventional anterior approach in one patient and with a new technique in two patients that allows preservation of urethra, uterus, vagina, and both ovaries.

The form of urinary reconstruction was ileal conduit (four patients), W-pouch with a serosal-lined tunnel (16 patients), double chimney (two patients), and T-pouch with a serosal-lined tunnel (two patients). The mean operating times for RRC and RRCP ranged from 110 to 170 minutes and 120 to 180 minutes for urinary diversion. The mean blood loss was 100 to 300 mL. All procedures were completed without intraoperative complications or conversion to laparoscopic or open surgery. None of the patients were given intraoperative blood transfusion. The number of lymph nodes removed ranged from 3 to 27, with one patient having N1 disease. The margins taken from the lower end of ureters were tumor-free. The margins of resection were free of tumor in specimen of all patients.

## Comments

In the last couple of years interest in laparoscopic radical cystectomy has increased, and approximately 150 such cases have been performed worldwide based on published articles and abstracts [21]. These procedures are not free of complications, however, and more so if diversion is performed totally intracorporeally. Menon and colleagues, after acquiring substantial experience in the field of robotic radical prostatectomy, expanded the horizon of robotic surgery in the field of bladder cancer and published their experience of large case series.

RRCP, RRC and urinary diversion is perhaps the most difficult robotic procedure performed to

Table 1

Current published articles on Robotic Radical Cystectomy and Urinary Diversion in the management of Bladder Cancer in English literature

Published Studies Reference (number)	Menon et al, [16]	Beecken et al, [22]	Menon M et al, [17]	Yohannes P [23]	Menon et al
Year & Journal	Feb. 2003, British Journal of Urology International	Sep. 2003, European Urology	April 2004, Journal of American College of Surgeons	Nov. 2003, Journal of Endourology	Personal communication, 2004
# of cases	14 Men,	1	3	2	24
Technique of Port's (#) placement	5-6 Ports	Minilaparotomy, 5 Ports	5-6 Ports	5	5-6 Ports
Lymphadenectomy	B/L EPLND	B/L PLND	B/L EPLND	B/L PLND	B/L EPLND; 3–27 lymphnodes removed, N1- 1 patient
Operation Time (min)	RRC – 140 UD-120(IC); 168 (ONB)	RRC + UD - 510	RRC-150,160,170 UD-130,190,170	10 and 12 hours	RRCP & RRC- 110 to 170 UD – 120 to 180
Blood Loss (CC)	<150	200	150,250,100	435 and 1800	100 - 300
Surgical Margins	Free of tumor Infiltration	Negative	Negative	In 1 case perivesical invasion	Free of tumor Infiltration
Urinary Diversion	Ileal Coduit – 2 W-Pouch neobladder-9 Double Chimney – 2 T Pouch - 1	UD- Hautmann ileal neobladder Midline incision was extended to exteriorized ileum for ileo-ileal anastomosis	Ileal Coduit – 1 W-Pouch neobladder-1 T Pouch - 1	In both cases ileal conduit was reconstructed	Ileal Coduit – 4 W-Pouch neobladder-16 Double Chimney – 2 T Pouch - 2
Intraoperative Complications or Conversion	None	None	None	None	None

B/L EPLND - Bilateral extended pelvic lymphadenectomy, IC- Ileal Coduit, ONB- Orthotopic neobladder, RRC- Robotic radical cystectomy, RRCP- Robot radical cystoprostatectomy, UD- Urinary Diversion.

date (although in some patients robotic radical prostatectomy may be equally challenging), but clearly this procedure can be done with excellent outcomes. There are two more reports published in the literature to date [22,23]. Table 1 summarizes the results of all the studies.

RRCP allows precise and rapid removal of the bladder with minimal blood loss, which translates to minimal morbidity with equivalent success to open surgery. Extracorporeal reconstruction of the urinary tract reduces operative time at this stage of laparoscopic and robotic instrumentation. An unanticipated benefit has been the early recovery of bowel function. With modern anesthetic techniques, most patients undergoing robot-assisted removal of their bladder are eating within 24 to 36 hours, and most are discharged within 4 to 5 days. The development of a technique for performing nerve-sparing RRCP using the da Vinci system is beneficial for sexually active male patients. The good results in terms of urinary incontinence also can result from excellent apical dissection, preservation of puboprostatic ligaments and sphincter urethra, good length of urethral stump, and urethrovaginoscopy performed robotically.

### Future directions

The challenge for the future is to continue to distinguish what can be done from what should be done. Long-term follow-up with cancer-free and overall survival and functional outcome is important, with comparison to the criterion standard of open surgery. With the development of technology, instrumentations, tissue engineering, and absorbable bowel stapler, and with further refinement of the technique, the entire procedure may be done completely intracorporeally with equal efficiency.

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## Robotic renal surgery

András Hoznek, MD<sup>a,\*</sup>, Jacques Hubert, MD<sup>b</sup>,  
Patrick Antiphon, MD<sup>a</sup>, Matthew T. Gettman, MD<sup>c</sup>,  
Ashok K. Hemal, MD, MCh, FACS<sup>d</sup>, Clément-Claude Abbou, MD<sup>a</sup>

<sup>a</sup>*Service d'Urologie, Centre Hospitalier Universitaire Henri Mondor, 51 Avenue du Ml. de Lattre de Tassigny,  
94010 Créteil-cedex, France*

<sup>b</sup>*Service d'Urologie, Centre Hospitalier Universitaire de Nancy-Brabois, Vandoeuvre les Nancy, France*

<sup>c</sup>*Department of Urology, Mayo Clinic, 200 First Street SW, Rochester, MN 55905, USA*

<sup>d</sup>*Vattikuti Urology Institute, Henry Ford Hospital, 2799 West Grand Boulevard, K-9, Detroit, MI 48202-2689, USA*

During the last decade, laparoscopic surgery has generated much interest in urology and has become an integral part of daily practice in many specialized centers. The learning curve of laparoscopy is steep, however, and for many established urologists in practice, fellowship training is unrealistic. Therefore, efforts have been made to develop alternatives that simplify the learning process and improve surgical efficiency. This explains the popularity of hand-assisted laparoscopy, a pragmatic choice for ablative surgery. This concept also partly explains the increasing interest in robotics in urology. To date, robot-assisted laparoscopic surgery has been used predominantly for radical prostatectomy because of the incidence of the disease and the advantages the robot offers for complex, advanced ablative and reconstructive procedures [1]. Robotic surgery also has been used for various other indications in urology [2,3].

This article reviews the present status and future prospects of robot-assisted laparoscopic renal surgery.

### Robotic nephrectomy

After the initial report of Gill and colleagues [4] on swine, Guillonnet [5] was the first to perform robot-assisted laparoscopic nephrectomy

in the human using the ZEUS system. The robot-assisted simple nephrectomy was performed successfully without complications through a five-port transperitoneal approach for a nonfunctioning hydronephrotic right kidney as a result of uteropelvic junction obstruction. In such interventions, the patient-side assistant has to perform several crucial tasks, including applying clips over the renal artery and the renal vein or the endovascular stapler and entrapping the surgical specimen in the organ retrieval bag at the end of the procedure. The operative time was 200 minutes, and blood loss was minimal.

### Robotic donor nephrectomy

There is one application in which the robot has had success. Over the past decade, laparoscopic donor nephrectomy has replaced the conventional open procedure in many transplant centers and likely will become the criterion gold standard soon. To decrease warm ischemia and improve the safety of the procedure, hand-assisted technique often is associated with the procedure. Although laparoscopic donor nephrectomy has revolutionized the process of renal donation, it has several disadvantages, including increased operating room time and the potential for shorter renal vessels than can be obtained with open donor nephrectomy [6].

Horgan and colleagues [7] reported the first 12 successful cases of hand-assisted robotic living-donor nephrectomies. They compared the results to standard laparoscopic and traditional open

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\* Corresponding author.

E-mail address: andras.hoznek@hmn.ap-hop-paris.fr (A. Hoznek).

procedures. All nephrectomies were left-sided. The authors concluded that the length of the dissected vessels, and therefore the quality of the allograft, is improved as a result of the dexterity enhancement of the robot. Overall operative time, however, was longest for the robotic procedures (mean 166 minutes) compared to the standard laparoscopic procedure (mean 110 minutes) or open donor nephrectomy (mean 95 minutes). The other outcome variables, including warm ischemia time, blood loss, and length of hospitalization, did not differ significantly when comparing standard laparoscopic and robot-assisted procedures. In addition, the cost of disposable instruments was similar among the minimally invasive treatment options.

In France, robot-assisted nephrectomy is performed routinely in the Hospital Brabois (Vandoeuvre les Nancy). Between November 2001 and February 2004, 38 nephrectomies (three for benign nonfunctioning kidneys, 11 donor nephrectomies, and 24 radical nephrectomies) were done in 31 patients (16 men and 15 women). The mean age of the patients was 45.2 years (range 18–76 years) and mean body mass index was 23.6 (range 19.5–30.4). The surgeon who performed all procedures had previous experience with robot-assisted pyeloplasties but limited experience with traditional laparoscopic surgery [8,9].

In the modest experience of Henry Ford Hospital (Detroit, Michigan) the Menon group has performed nephrectomy, nephroureterectomy, partial nephrectomy, radical nephrectomy, and radical nephrectomy with repair of minor rent in inferior vena cava (IVC).

### Technique of radical nephrectomy

#### *Step 1: patient positioning*

Under general anesthesia, the patient is placed in a well-padded lateral kidney position (45°–60°) with the ipsilateral (diseased) side up. A pillow is placed between the knees and the arm is placed on an armboard. All pressure points are well padded. A Foley catheter and oro-gastric tube are placed.

#### *Step 2: port placement*

Pneumoperitoneum is established using a Veress needle (Ethicon Endosurgery, Albuquerque, New Mexico). A 12-mm camera port is placed in the midclavicular line lateral to the rectus muscle at the level of umbilicus, and, in some patients, at the umbilicus (see article by Hemal et al., on port

placement elsewhere in this issue for further discussion). Next, the two 8-mm robotic ports are placed under vision. They are equidistant from the camera port in a right-angle configuration. Two additional ports are placed for the assistants: a 5-mm and a 10- or 12-mm port. These ports are needed for the patient-side assistant for suction/irrigation, retraction, countertraction, and to introduce the Hem-o-lok clip (Weck Closure System, Research Triangle Park, North Carolina) applicator or endovascular stapler for clipping of the renal vessels. The key point in port placement is that the robotic ports should be placed as far as possible from each other because it helps subsequently in wide excursions. This is important in kidney surgery during the bowel mobilization especially, and to mobilize the kidney after control of the renal artery and vein.

#### *Step 3: installation of the robot*

The robotic arms are draped in the regular way. The camera is black-and-white balanced and calibrated. After the ports are placed, the robot is docked from the patient's back at an angle of 60° to the head end of the table to permit accurate positioning of the camera arm and two working arms. In thin, short individuals, it can be docked from the back of the patient. After docking, the two robotic arms are lateralized to provide maximum range of motion. This varies according to build and stature of the patient, however.

#### *Step 4: peritoneoscopy*

An initial evaluation of the abdominal cavity is performed to evaluate for metastatic disease and adhesions.

#### *Step 5: incision of the line of Toldt and mobilization of the colon*

Using an Endowrist long-tip forceps and permanent cautery hook, dissection is started by incising the line of Toldt lateral to the right or left colon and bringing down the ascending or descending colon according to side of the renal involvement. The mobilization of the colon should occur at the same level throughout its length; caudally, the colon should be mobilized to the level of iliac vessels, and cranially, the kidney should be made free to the level of liver or spleen.

For the right side, the fascial attachments from the colon to the liver should be freed. The colon then should be swept medially taking care of small vessels, lymphatics, and fascial structures. The

liver is freed by dividing the triangular ligament. Then the duodenum is mobilized with the Kocher maneuver to expose the IVC.

In left radical nephrectomy, the line of Toldt should be incised to the level of the spleen. The fascial attachment to the spleen is freed. It is preferred to not take down the splenic flexure between the spleen and colon because once the plane is developed between the spleen and superior pole of the kidney, both structures fall medially.

#### *Step 6: control of renal artery and vein*

For the right side, liver adhesions are released and the right lobe of the liver is elevated with a fan retractor placed through the 5-mm port. Similarly, on the left side, retraction of the spleen is needed. The gonadal vein can be traced to the IVC on the right side and to the left renal vein on the left side. Next, the gonadal vein and the ureter are identified at the pelvic brim, clipped, and divided. On the right side, medially, the IVC can be identified easily and dissection then is undertaken along the IVC superiorly. On the left side, the adrenal vein should be dissected entering into the renal vein, whereas on the right dissection proceeds to the IVC. The renal vein and artery should be cleaned off carefully. The authors most often found two renal arteries and two renal veins. Before dividing these vessels, the adrenal, gonadal, and lumbar veins (if needed) are controlled with the clips. The renal artery and renal vein can be divided by any of the following techniques: (1) Hem-o-lock clips, (2) endovascular stapler, or (3) tying the vessels with the sutures (as robotic assistance provides the opportunity).

#### *Step 7: mobilization of the kidney*

An effort is made to maintain the plane of the dissection external to Gerota's fascia at all times. Next, the inferior and superior poles of the kidney are mobilized, avoiding a breach in Gerota's fascia. Finally, the posterior attachments are freed. In patients who have upper- and middle-pole tumor, adrenalectomy is performed. If one plans to spare the adrenal gland, then the plane should be developed between the upper pole of the kidney; otherwise, it should be removed en bloc with the kidney.

#### *Step 8: retrieval of the specimen*

After complete mobilization, the specimen is placed in an EndoCatch II bag (US Surgical, Norwalk, Connecticut) or in LapSac (Cook,

Spencer, Indiana). The field is irrigated and hemostasis is secured. Pneumopressure is lowered to 5 mm Hg to ensure final control of bleeding because high working pressure (15 mm Hg) during surgery may have tamponed the bleeders. A 15F Jackson-Pratt drain is inserted through the lateral robotic port site. The port site incision is enlarged to retrieve the EndoCatch II bag containing the specimen. After retrieval of the specimen, the wound is closed in layers.

### **Donor nephrectomy**

The technique of left donor nephrectomy differs slightly because warm ischemia has to be avoided. After dissection of the renal pedicle, the perirenal fat is removed from the anterior surface of the kidney. Then, the convexity and the posterior aspect of the kidney are dissected; the adrenals are left intact. The ureter is dissected with a sufficient amount of periureteral fatty tissue and the gonadal vein; it then is clipped and sectioned. A 15-mm Endocatch is inserted through a suprapubic incision and brought near the kidney. Only at this time are two clips placed on the artery, and then the vein is ligated and clipped on the right side of the aorta if feasible, thus gaining maximal length of vessels at the site of the kidney. In order not to shorten the renal vessels, no clips are placed on the vessels on the renal side. The kidney is entrapped in the Endocatch and extracted. It is perfused and cooled immediately.

After lowering the insufflating pressure and checking for hemostasis, a nonabsorbable 6-0 running suture on the artery stump offers additional safety to the procedure (Fig. 1), however, it is not mandatory. Living-donor nephrectomy is performed only rarely on the right side. Its principles are similar to that of radical nephrectomy, but with some specificities, such as entire dissection of the kidney and ligation of the ureter before ligating and sectioning the renal vessels and avoiding clips on the renal side.

### **Results**

In this series, mean operative time was 175.5 minutes and 154.6 minutes for right and left radical nephrectomy, respectively. Live-donor nephrectomy required an average of 181 minutes and bilateral nephrectomy (performed in dialysed or transplanted patients with pathologic native

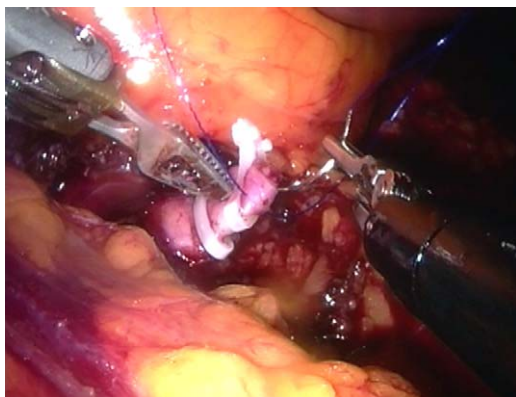


Fig. 1. A nonabsorbable 6-0 running suture on the artery stump is easy to perform with the robot and optimizes safety of nephrectomy.

kidneys) needed 221 minutes. Two thirds of the patients had one renal artery and one third had two or more renal arteries. Intraoperative complications consisted of one splenic injury and one colonic serosal injury; both could be repaired using the robot. Only one patient (2.6%) required conversion because of severe postinfection perinephritis and difficulties progressing in dissection. No transfusions were necessary; the average drop in postoperative hemoglobin level was 0.6 g/dL.

In the experience of Henry Ford Hospital (Peabody and colleagues, unpublished data, 2004), one patient had a tear in the IVC, which was repaired, and the entire procedure, including suturing of the IVC tear, was completed with robotic assistance without conversion to open surgery. The operative time (insertion of Veress needle to skin closure) was 187 minutes and the console time was 132 minutes. Intraoperative blood loss was 200 mL.

All transplanted kidneys functioned immediately after live donor nephrectomies.

### The rationale of robot-assisted nephrectomy

The main advantage of robotic telemanipulators during laparoscopic surgery is the simplification of advanced reconstructive tasks involving suturing and knot tying. This is the reason that robotic radical prostatectomy or pyeloplasty is accepted increasingly by the urologic community. Yet, in the standard technique of laparoscopic nephrectomy, such skills are not essential because ligation and division of the renal hilum is performed using surgical clips and a gastrointestinal

anastomosis (GIA) stapling device. Malfunction of these devices has been reported, however [10]. These are rare complications, but when they occur, they may have severe consequences. Ligation of the vein and applying hem-o-lock clips instead of endo-GIA or metallic clips avoid these incidents. Additionally, in the robotic technique, performing a running suture on the renal artery stump can provide increased safety.

In addition, surgeons with no prominent previous laparoscopic training can perform these tasks easily. For urologists with access to surgical robots and experience with robotic pyeloplasty or prostatectomy, performing different types of nephrectomy is a reasonable choice.

### Robot-assisted renal transplantation

Besides dexterity enhancement, another feature that characterizes robotic surgery is the ability to dissociate the surgeon from the operative field. This has a potential application in hostile environments [11] and in conditions when direct contact with the patient exposes the surgeon to viral transmission. In urology, such professional hazards are met when dealing with hemodialysed patients [12]. The first robot-assisted kidney transplantation in a human was reported by Abbou and colleagues [13]. A right cadaveric kidney was transplanted for a 26-year-old male patient who had been on hemodialysis for 11 years. The surgery was performed with the help of the da Vinci robot by a remote surgeon, who entirely performed the vascular dissection and anastomosis as well as the ureterovesical anastomosis. Operative time was 178 minutes. Renal perfusion was excellent with an immediate diuresis. The patient had postoperative acute tubular necrosis that started to resolve after 1 week. Robotic assistance made possible the anastomosis with its unique ability of stereoscopic magnification and ultraprecise suturing techniques because of the flexibility of the robotic wristed instruments.

### Current limitations of robotic surgery, future prospects

Despite increasing interest and the development of procedures with proven safety and feasibility, many surgeons believe that robotics is not ready for prime time at most centers. This is explained by technical limitations and financial barriers.

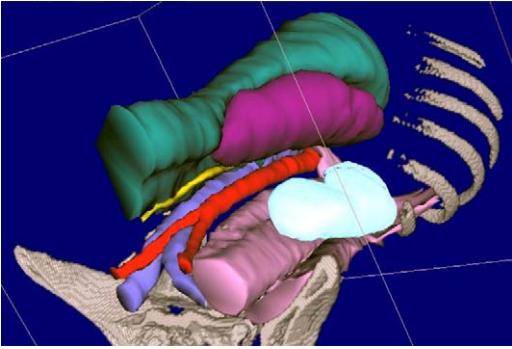


Fig. 2. Three-dimensional virtual anatomic model obtained after segmentation. Light blue indicates anatomic position; violet indicates kidney displaced as a result of pneumoretroperitoneum.

It is not unrealistic to expect, however, that surgical robots will undergo a development similar to other fields of computing and telecommunications. For example, the world's first gigabyte-capacity disk drive, the IBM 3380, introduced in 1980, was the size of a refrigerator, weighed approximately 250 kg, and cost \$40,000. Such storage capacity costs today less than \$1. In many fields of contemporary medicine, routine practice has become inconceivable without computer-based systems. For example, surgeons consider CT scan data to be more reliable in making diagnoses than classic information such as physical examination, symptoms review, or history taking.

But robots go beyond the category of specialized laparoscopic instruments. The emerging combination of high-precision robotic manipulators and new cross-sectional imaging techniques opens the horizon of presurgical planning with the help of a virtual model. The authors have been involved in a project of robot-assisted kidney surgery modeling [14]. A preliminary step of this process consists of reliable patient data collection. This is achieved using CT scan or MRI images with a method termed *segmentation* that produces a three-dimensional anatomic model (Fig. 2).

Then, a computerized optimization algorithm (Simulation and Transfer Architecture for Robotic Surgery [STARS]) indicates the best conditions based on a set of predefined criteria that reflects the anatomy of the patient, the available instruments, and the requirements of the intervention (Fig. 3).

As a result, the system suggests the best possible port placement and positioning of the robot that will offer optimal handling of surgical

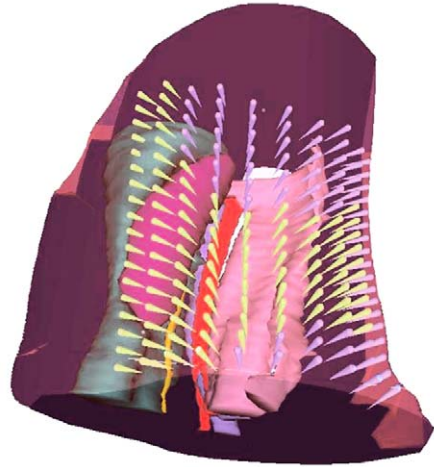


Fig. 3. All possible entry points of trocars.

targets with the most favorable ergonomics and visibility of the zones of interest, and avoids instrument collisions (Fig. 4). In addition, this virtual model allows presurgical training and rehearsal [15].

### Summary

Robotic technology is an expansion of laparoscopic surgery. Robots can be conceived of as specialized laparoscopic tools; their aim is to improve dexterity of the operating surgeon, and therefore they correspond to computer-enhanced telemanipulator devices. For the patient, the

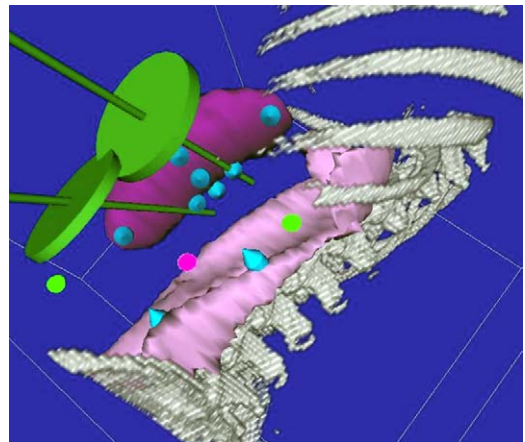


Fig. 4. Most favorable instrument positions. Light-blue plots display the surgical target areas.

advantage of robotic surgery is essentially the advantage of the laparoscopic approach. It gives surgeons tremendous benefits, however, with its intuitive Endowrist and dexterity. From the patient perspective, the biggest difference is between an open operation and one that uses minimally invasive techniques. The contribution of robotics to the evolution of surgery will be obvious if these new systems increase the number of conventionally trained surgeons performing more complex operations using minimally invasive surgical techniques, or if the outcome data from different centers worldwide suggest that the use of advanced technology permits surgeons to have augmented technical performance.

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## Robotic pyeloplasty: technique and results

Reinhard Peschel, MD<sup>a,\*</sup>, Richard Neururer, MD<sup>a</sup>,  
Georg Bartsch, MD<sup>a</sup>, Matthew T. Gettman, MD<sup>b</sup>

<sup>a</sup>*Department of Urology, University of Innsbruck, Anichstrasse 35, A-6020 Innsbruck, Austria*

<sup>b</sup>*Department of Urology, Mayo Clinic, 200 First Street SW, Rochester, MN 55905, USA*

Over the last 15 to 20 years, various endopyelotomy techniques (antegrade, retrograde, ureteroscopic, Acucise) were introduced as less-invasive alternatives to the criterion standard technique of open pyeloplasty [1–3]. Although the techniques of endopyelotomy have reduced length of hospitalization, degree of postoperative disability, and length of convalescence, the overall success rates have been lower than those reported with open pyeloplasty. Since the first description of the technique by Schuessler and colleagues [4] in 1993, laparoscopic pyeloplasty has become an established procedure for treatment of ureteropelvic junction obstruction (UPJO) [5–9]. When compared with other UPJO treatments, laparoscopic pyeloplasty consistently has been associated with benefits of minimally invasive surgery and success rates equivalent to open pyeloplasty [4–9]. Laparoscopic pyeloplasty is a versatile technique suitable for patients who have intrinsic obstruction, high ureteral insertion, a redundant renal pelvis, or crossing vessels, but the technical difficulty of intracorporeal suturing has limited its widespread clinical application [6].

By integrating computer-enhanced robotic technologies with the technical skill of the surgeon, the goals of advanced robotic systems are to improve operative technique, simplify intracorporeal suturing, and increase applicability of advanced surgical techniques such as laparoscopic pyeloplasty. This article describes the technique and initial results for robotic pyeloplasty.

### Preoperative evaluation

Preoperatively, patients are diagnosed with UPJO on the basis of presenting symptomatology and radiographic studies. Standard diagnostic studies for UPJO include an excretory urogram and a diuretic nuclear renogram. In select cases, a diagnosis of crossing vessels can be established using CT or color Doppler ultrasonography [8]. All patients must have sterile urine, normal coagulation studies, and a satisfactory preoperative medical evaluation before surgery.

The indications for robotic pyeloplasty are essentially the same as those for laparoscopic pyeloplasty. Robotic pyeloplasty can be performed safely for patients who have primary UPJO and secondary UPJO after failed endopyelotomy. Various anatomic presentations likewise can be treated with robotic pyeloplasty, including patients who have intrinsic or extrinsic obstructions, high ureteral insertions, a redundant renal pelvis, or crossing vessels. Patients who have poor renal function or a small intrarenal pelvis, or who have failed open pyeloplasty previously, are not candidates for robotic pyeloplasty.

### Surgical technique

Using the da Vinci robotic system, all steps of traditional Anderson-Hynes dismembered pyeloplasty, YV-plasty, and nondismembered Fenger-plasty can be performed [6,7,9]. A standard set of laparoscopic instruments is required in addition to the robotic instrumentation required for the da Vinci robot. For robotic pyeloplasty, four interchangeable robotic instruments are used: monopolar hook electrocautery, Cadiere forceps, needle drivers, and round-tipped scissors.

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\* Corresponding author.

E-mail address: reinhard.peschel@uibk.ac.at  
(R. Peschel).

### *Patient positioning and initial patient preparation*

The patient is placed in a modified 45° lateral decubitus position. The patient is secured carefully to the operating room table after making sure all extremities are well padded. A standard skin preparation is performed from the xiphoid process to the pubic symphysis.

### *Access and port placement*

All robotic pyeloplasty procedures are performed using a transperitoneal approach. After establishing pneumoperitoneum with a Veress needle, four ports are placed. The working arms of the robot are placed through 8-mm reusable ports (Intuitive Surgical, Mountain View, California) and the robotic camera arm is placed through a 12-mm standard laparoscopic port (Ethicon Endo-Surgery, Cincinnati, Ohio). The assistant surgeon controls traditional laparoscopic instruments through an additional 12-mm standard laparoscopic port (Ethicon Endo-Surgery).

The 12-mm port for the camera is placed at the umbilicus. The 8-mm ports for the working robotic arms are placed midway between the umbilicus and the xiphoid process in the midline and paraectally below the level of the umbilicus. The 12-mm assistant port is placed at least 5 cm below the umbilicus in the midline (Fig. 1). The ports are placed optimally such that at least a handbreadth separates each working arm from the camera arm.

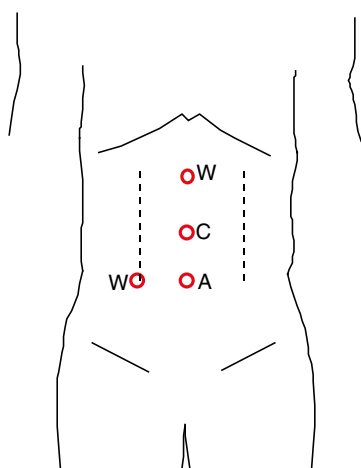


Fig. 1. Port placement for robotic pyeloplasty. (W) 8-mm working port, (C) 12-mm camera port, (A) 12-mm assistant port.

### *Exposure of the ureteropelvic junction obstruction*

For patients who have right-sided UPJO, the line of Toldt is incised and the hepatic flexure is retracted medially to identify Gerota's fascia. For patients who have left-sided UPJO, the standard approach similarly involves incision of the line of Toldt and medial mobilization of the descending colon to expose Gerota's fascia. For thin patients who have a left-sided UPJO, an alternative transmesenteric approach can be used. Gerota's fascia then is incised carefully for dissection of the UPJO and associated crossing vessels.

### *Pyeloplasty and stent placement*

Preoperative and intraoperative findings are helpful in selecting a specific pyeloplasty technique. Robot-assisted Anderson-Hynes pyeloplasty is the preferred approach for patients who have a large renal pelvis or a high ureteral insertion, or for patients who have posterior crossing vessels at the UPJO. The UPJO is transected, the ureter is spatulated on the lateral side, and the redundant renal pelvis is excised. At least three 4-0 vicryl sutures are used to perform the repair. The sutures are introduced into the abdomen by the assistant surgeon through the assistant port. Using the da Vinci robotic system, the first intracorporeal suture is placed through the apex of the spatulated ureter and the most dependent aspect of the renal pelvis and tied. Subsequently, two additional running 4-0 vicryl sutures are used to perform the posterior and the anterior anastomosis. After the initial throws are performed on the anterior anastomosis, a 7F double-pigtail stent (26–30 cm long) is placed in antegrade fashion over a guidewire through the assistant port by the scrubbed surgeon. The pyeloplasty is finished after the renal pelvis is closed using additional running 4-0 vicryl sutures. As a time-saving measure, the assistant surgeon applies traction to the suture after each throw and cuts the suture after intracorporeal knots are placed.

For patients who have a smaller, more dependent renal pelvis or for patients who have anterior crossing vessels, a robot-assisted YV-plasty or Fenger-plasty technique can be performed [9]. Anterior crossing vessels first are dissected free from the UPJO and then are displaced superiorly. The displaced crossing vessels are secured to the renal pelvis using 4-0 polydioxanone sutures. When performing a YV-plasty, the UPJO is incised in a Y-shaped fashion and, similar to an Anderson Hynes

pyeloplasty, a 7F double-pigtail stent is inserted in antegrade fashion over a guidewire. The incision then is closed in a “V” shape using one interrupted suture for the apex of the pelvis and two running sutures for the anterior and posterior anastomosis. Performing a Fenger-plasty, the UPJO is opened in longitudinal fashion with round-tipped robotic scissors. Again, a 7F double-pigtail stent (26–30 cm long) is placed in antegrade fashion over a guidewire. The incision then is closed transversely with three to five interrupted 4-0 vicryl sutures.

### Closure

In all cases, displaced bowel is repositioned in anatomic fashion and secured with one 4-0 vicryl interrupted suture. In select cases, a surgical drain is placed after performing pyeloplasty. The fascia and skin then are closed in standard fashion at each laparoscopic port site.

### Postoperative course

A short hospitalization is associated with robotic pyeloplasty. The urinary catheter typically is removed on the second postoperative day. The double pigtail stent is left indwelling for 6 weeks. At 3 months' follow-up, objective assessment of the repair is performed with excretory urography or diuretic nuclear renography.

### Results

Between June 2001 and March 2004, 49 patients who had UPJO underwent robotic pyeloplasty. Ten of these patients had previous failed endopyelotomy. In two cases, a Fenger-plasty was performed, in seven cases a YV-plasty, and in 40 cases, Anderson-Hynes dismembered pyeloplasty was the method of choice. The mean operative time, including the set-up of the robot, was 124 minutes (range 72–215 minutes). No intraoperative complications or open conversions occurred. The estimated blood loss was less than 50 mL in all cases. Postoperatively one patient required open repair of a leakage of the renal pelvis away from the anastomosis.

Follow-up is available for 41 of the 49 patients. Mean follow-up is 7.4 months (range 3–32 months). All operations were successful with no evidence of obstruction in the diuretic renal scans or intravenous pyelogram.

### Discussion

The experimental groundwork for robotic pyeloplasty was performed by Sung and colleagues [10] in the porcine model using the Zeus robotic system (Intuitive Surgical). In the study, farm pigs were randomized prospectively to laparoscopic pyeloplasty performed with or without telerobotics. In comparing the robotic and standard techniques for laparoscopic pyeloplasty, no significant differences in total operative time, anastomotic time, or number of suture bites for each ureter were observed. Based on these results, those authors concluded that robotic pyeloplasty was feasible and had implications for clinical application. In a related experimental study comparing the da Vinci robot to the Zeus robot, Sung and Gill [11] reported da Vinci-assisted pyeloplasty was associated with shorter overall operative times, shorter anastomotic times, and an increased number of suture bites per ureter. Those authors concluded that the da Vinci robotic system was more intuitive than Zeus, but that either system was effective for robotic procedures.

Clinical experience with robotic pyeloplasty subsequently has been reported with the da Vinci system. In an initial series of nine patients undergoing da Vinci-assisted laparoscopic Anderson-Hynes pyeloplasty, Gettman and colleagues [12] reported an overall operative time of 139 minutes and an anastomotic time of 62 minutes. In a related study comparing standard laparoscopic pyeloplasty to robotic pyeloplasty, shorter overall operative and anastomotic times were associated with the da Vinci-assisted laparoscopic procedures [13]. Bentas and colleagues [14] also reported their initial experience of da Vinci-assisted laparoscopic Anderson-Hynes pyeloplasty. Among the cohort of 11 patients, those authors reported a mean operative time of 197 minutes with no intraoperative complications, no open conversions, minimal blood loss, and a 100% success rate at 1-year follow-up.

Several advantages have been reported when using telerobotics to assist with complex laparoscopic reconstructive procedures such as pyeloplasty. For instance, Bentas and colleagues [14] had no experience with laparoscopic pyeloplasty before embarking on their da Vinci-assisted procedures. In general, they concluded that telerobotics enabled inexperienced urologists to perform complex reconstructive procedures with more confidence and better results than could be obtained with standard laparoscopy. Using

experimental models, Yohannes and colleagues [15] have demonstrated that the learning curve associated with intracorporeal suturing is shorter with the da Vinci robotic system than with standard laparoscopy. Furthermore, the group found that novice laparoscopists had shorter learning curves than experienced laparoscopists. In a case report highlighting the technical considerations of da Vinci–assisted laparoscopic Anderson-Hynes pyeloplasty, Yohannes and colleagues [16] also concluded that telerobotics simplified intracorporeal suturing and may expand applicability of laparoscopic pyeloplasty to urologists inexperienced in laparoscopy. Subjectively, the authors also found that an optimally positioned da Vinci robot can decrease the difficulty of intracorporeal suturing. Furthermore, the authors found the da Vinci robotic system provides an ergonomic environment that can minimize surgeon fatigue.

Despite the touted benefits associated with telerobotics, several technical and nontechnical disadvantages deserve comment. Although telesurgery may simplify the learning curve for intracorporeal suturing, a significant learning curve is associated in general with the use of telerobotic devices. Because the primary surgeon is removed physically from the operating table, effective intraoperative communication and reliance on a team approach are critical to the success of the procedure. In addition, the present robotic technology is bulky and can be difficult to position optimally. These types of learning curves can be minimized by performing da Vinci–assisted procedures in familiar surroundings and by using a surgical team familiar with the robotic device. In addition, because force-feedback is not a characteristic of the current robotic technology, performing the laparoscopic maneuvers with the da Vinci robot requires increased attention to visual rather than tactile cues. In reality, this factor is a minimal concern as more experience is accrued with telerobotics. Body habitus is another factor that can limit the effectiveness of robotic pyeloplasty. Performing robotic pyeloplasty can be more difficult for small patients because the distance between the trocars (and the distance between the robotic arms) is reduced. As the distance between trocars decreases, the exchange and alignment of the instruments can become more tedious. Also, because the robotic arms are not secured to the operating table, the patient cannot be moved on the operating table until the robotic arms are released.

One of the biggest nontechnical limitations to the widespread application of telerobotics is cost. The da Vinci robotic system, for instance, has an initial cost of \$1.4 million and also is associated with a high cost of disposable instruments. As clinical experience increases and newer robotic instrumentation is introduced, it is anticipated that the costs associated with telerobotics will decrease. Furthermore, all robotic pyeloplasties (and other telerobotic procedures) currently require the presence of two urologists. In theory, this requirement adversely impacts the health care delivery system. Lastly, opportunities for education and training in laparoscopy and telerobotics must increase to promote increased use of robotics in urology.

## Summary

The da Vinci robotic system can be used to perform dismembered and nondismembered pyeloplasty techniques effectively. Robotics not only seems to improve dexterity and surgical precision but also provides an ergonomic surgical environment for a surgeon performing complex reconstructive procedures such as pyeloplasty. Although performance-enhancing features of the da Vinci robot seem to decrease the difficulty of intracorporeal suturing, a learning curve also exists for telerobotic procedures. This learning curve may decrease as experience with telerobotics increases and as advances in technology are introduced. Presently, the interaction between the primary and assistant surgeon seems crucial to the success of the procedure. Although the early clinical experience with robotic pyeloplasty is favorable, continuing clinical evaluation and careful follow-up are required to determine if the procedure is as efficacious in the long run as open pyeloplasty and laparoscopic pyeloplasty.

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# Robotically assisted surgery in pediatric urology

Craig A. Peters, MD, FACS, FAAP

*Department of Urology, Children's Hospital Boston, Harvard Medical School, 300 Longwood Avenue,  
Boston, MA 02115, USA*

Robotic devices in laparoscopic surgery offer the potential to overcome many of the impediments to the development of laparoscopic techniques in pediatric surgical applications. Pediatric uses for reconstructive laparoscopic procedures have developed slowly, largely because of the need for high precision that may not be achieved readily in conventional laparoscopic methods [1]. The limited number of surgeons able to move through the extensive learning curve and improve their ultimate efficiency will continue to limit the ability to capture the benefits of laparoscopy in the pediatric patient. Robotics may permit delicate reconstruction in a wide variety of situations without having to pass through the learning process, and may improve outcomes for the experienced laparoscopist. It is also possible that more complex reconstructive procedures that would not be undertaken laparoscopically would be performed with robotic assistance.

Available robotic systems have characteristics that may improve surgical outcomes, including high-resolution three-dimensional vision, tremor-filtered instrument control with movement scaling, and highly dexterous wrist-like movements of the end-actuators that permit a degree of instrument access beyond any conventional laparoscopic tool. These characteristics are the core advantages of robotic technology in laparoscopy, and can benefit the pediatric patient.

The goal of robotic surgical assistance in pediatric urology is to gain the advantages of laparoscopy in pediatrics, including reduced incisional size and morbidity, shorter hospital stay, and a less painful and more rapid recovery, without sacrificing reconstructive precision.

Although these advantages may be difficult to prove with small numbers in the young pediatric patient, they seem evident in the school-aged and older child. In gaining this advantage, laparoscopy cannot limit the efficacy of the surgery, and robotic assistance seems able to match the efficacy of open surgery, if not enhance it.

## Pediatric issues

The robotic devices used in children are identical to those used in adults, but several aspects of their use must be adjusted for when used in children.

## Operating room team

More so than with adults, the efficiency of the surgical team using the robotic device is critical to the safe performance of the procedure in children. All members need to have had dry-laboratory training to understand the movements of the system, its mode of action, and the methods for instrument changes. A dedicated nursing team is essential and should be involved and integrated with the procedure closely. As with open surgery, it is essential for them to know the procedural steps and requirements to anticipate needed instruments, sutures, and actions of the surgeon.

The role of residents is evolving as new procedures are being developed; it is difficult to justify their direct performance of the procedure, but it is essential that they are involved in the surgery to permit progressive dissemination of the technology and facility with it. The author's team always has a patient-side surgeon scrubbed to anticipate any emergency while the operating surgeon is not scrubbed. This surgeon is usually a resident who is interested in participation. This

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*E-mail address:* [craig.peters@childrens.harvard.edu](mailto:craig.peters@childrens.harvard.edu)

can generate some conflict with the need for the nursing staff to develop their skills in instrument management. A continuing training and refresher laboratory program is helpful for surgeons, nurses, and residents.

### *Set-up*

Usually the robot is set up as the patient is being put to sleep and during the performance of a cystoscopy, if appropriate. Along with the necessary robotic devices to be used, the author's team has an emergency set-up tray for open surgery as well as a few basic, nondisposable laparoscopic instruments available in the room in case an urgent conversion or adjunctive conventional laparoscopic manipulation is needed. All aspects of the robotic system are turned on and checked before beginning the procedure. This can be accomplished in 15 to 20 minutes and should incur little delay in the overall procedure. A bladder catheter usually is used, although this may be placed on the sterile field if bladder filling and emptying is needed during the procedure. A rectal tube should be placed for pelvic surgery to decompress the recto-sigmoid. The anesthesia team needs to be aware of the positioning of the robot in children, where the relative spaces can be small, and clearance room for the robotic arms is needed.

### *Patient positioning*

Patient positioning is important as well. The degree of patient tilt should be adjustable to permit fine-tuning of positioning once the operative area is seen. In some cases the kidney may be accessed transmesenterically, and therefore the patient does not need to be tilted steeply, whereas if the colon needs to be reflected, at least 60° of tilt is needed. For bladder or pelvic procedures, the robot typically is brought in from the patient's feet. Placing the patient in the Trendelenberg position to provide a better exposure of the pelvic organs is important and must be done before engaging the robot. Once the robotic arms are engaged, the patient may not be moved without disengaging the robotic device.

### *Port placement*

Port position for laparoscopic procedures is of paramount importance in children, where the working space is limited and area within which to place the robotic cannulae is small. The general rule of four fingerbreadths between the ports is impossible to apply in an infant whose abdomen is only

that wide. The most important rule is to create a symmetric array of the ports relative to the operative site. The camera is the central axis aiming at the site of work, and the two working ports need to be positioned evenly, equidistant from the line between the camera and the operative site. In renal surgery this is essential, and the upper port often needs to be in the midline, whereas the lower quadrant port is in the midclavicular line (Fig. 1). If the arms are not nearly symmetric, one arm likely will have a limited range of movement or will impede the camera arm.

### *Working space*

In small children the actual working space, even for transperitoneal procedures, is small and great care must be taken to avoid inadvertent injury to intra-abdominal structures. Instruments always should be introduced under vision or after inspecting their pathway visually. Instruments should not be used or manipulated unless they may be monitored under direct vision. Reinsertions are usually safe because the system returns the instrument to its previous location based on the position of the tip of the instrument; therefore they should be straightened before removal for replacement. The surgeon needs to develop a mental image of the operative field and its immediate

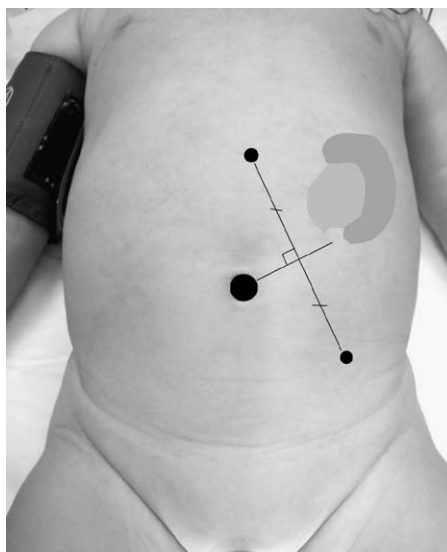


Fig. 1. Port arrangement for robotically assisted renal surgery, particularly for pyeloplasty. The arrangement of the arms and camera port is oriented symmetrically toward the area of surgery.

surround and have a sense of where the instruments can be placed.

The retroperitoneal space is challenging to develop for the robot, but the working space needed is usually small for such cases (eg, pyeloplasty). It may be developed with the endoscope or the balloon. It is preferable to develop the space, position the patient, and then engage the robot.

### *Instruments*

Both 8- and 5-mm working instruments are available for the robotic system. The three-dimensional scope for the system is 12 mm in size and fits through a conventional laparoscopic cannula, usually placed in the umbilicus. An adapter for mounting a 5-mm two-dimensional endoscope is available as an addition to the robotic device. The visual advantage of the three-dimensional image is significant for suturing and knot tying. It is less important for the simple dissection of some procedures, but essential for a complicated reconstruction such as a pyeloplasty.

The instruments typically needed for renal and bladder applications include a grasping device, such as the DeBakey forceps or the 5-mm Maryland dissector. These are useful, all-purpose instruments for tissue manipulation, dissection, and control. It is rare to need the larger graspers, which seem better suited for moving larger tissues such as the bowel or bladder as a whole.

The hook cautery is used for all dissection because none of the other instruments are electrified. The 8-mm version is large for delicate use and seems to work more efficiently when pushed instead of pulled with the hook. The smaller, 5-mm version is more delicate and functions more efficiently. With higher cautery settings (ie, over 25 on most instruments) the hook cautery works well with the hooking action, but these settings are usually too high for pediatric applications.

The scissors for 8- and 5-mm sizes are straight and nonelectrified. They are used almost exclusively for cutting suture. The 8-mm needle drivers come in two sizes: large and fine (microtip). The microtip needle drivers are needed for sutures of 4-0 and below, yet are sharply pointed and must be used carefully. The large needle driver can handle 4-0 sutures and larger and is fairly blunt. Neither size is useful for holding tissue even briefly. As a result, it is sometimes necessary to use one in concert with a DeBakey forceps to permit efficient tissue positioning while suturing, but the DeBakey is not useful for tying because it will fray sutures quickly.

Therefore, it should be used in this way only on the tail end of a running suture or the suture being used for multiple knots. There is no device to cut the suture after tying to permit quickly placing another stitch and tie; therefore, the scissors must be introduced to cut the suture. This slows the flow of the procedure. A needle driver with scissors in the jaw would be a valuable new instrument. The 5-mm needle drivers are useful for sutures up to 3-0 and seem to handle delicate sutures of 6-0 well. They are more efficient for tissue holding and seem more versatile. A manual-reload clip applier is available, but is limited by the need for removing the instrument and reloading. The author's team uses either the standard 5-mm multifire disposable clip applier when multiple clips will be needed, or suture ligation, as when controlling the renal vessels.

The 5-mm instruments are controlled with a slightly different mechanism than the 8-mm instruments, which move on a pulley-and-cable basis. The 5-mm instruments are moved by cables and a gooseneck-type system near the working tip. This requires greater linear distance along the instrument to actuate the angulation of the tip. In small working spaces, this may create a problem (Fig. 2).

### **Renal applications**

The ideal application of the robotic system in children seems to be dismembered pyeloplasty and partial nephrectomy where delicate suturing is



Fig. 2. The 5-mm instruments require more room than the 8-mm instruments to move the instrument into a right angle, which may limit movement in a confined space. (Courtesy of Intuitive Surgical, Sunnyvale, CA; with permission.)

needed. The author believes there is benefit in the performance of simple nephrectomy as well, based on the enhanced visualization and control of the instruments, particularly during control of the renal vasculature. Suture ligatures may be used readily with efficiency and avoiding clips.

For any of these procedures, access to the kidney may be transperitoneal or retroperitoneal. Each has advantages. For smaller children, the transperitoneal approach permits more working space for manipulation, although there is always the concern for injury to the intraperitoneal structures. Similarly, intraperitoneal adhesions are a concern, but have not been reported to any degree. For infants with uteropelvic junction (UPJ) obstruction, the transperitoneal approach may have an advantage in that the renal pelvis is accessed readily through the mesentery, which contains little fat. Often the pelvis is visible immediately on entry into the peritoneal space and the UPJ may be directly evident (Fig. 3). The amount of tissue disruption with dissection is minimal because the area of surgery is exposed in minutes with no manipulation of the perinephric tissue planes. This is less amenable to placing a drain, and most of these patients have a double-J ureteral stent placed, which has advantages and disadvantages as well.

For partial nephrectomy with associated ureterectomy, the transperitoneal approach provides access to all parts of the operative field without repositioning the robot. Retroperitoneal partial nephrectomy is limited by the amount of ureter readily removed from one port positioning. In a nonrefluxing situation, this may be of no conse-

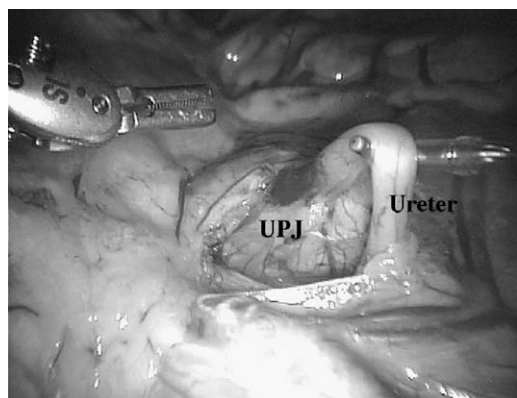


Fig. 3. Appearance of the ureteropelvic junction in a child transmesenterically. The bulging renal pelvis is evident.

quence. The author has performed several combined nephrectomies and contralateral ureteral repairs for reflux for which the transperitoneal approach is ideally suited. Retroperitoneal access to the kidney is the more natural approach for the urologist, limits the potential problems of urinary extravasation and inadvertent bowel injury, and provides direct access to the kidney. This has been the author's favored approach for conventional laparoscopy, but the robotic system is more difficult to use in this position. It can be accomplished, and will be developed with the 5-mm instrumentation now available. It has been used in some centers with excellent results in older children.

Again, the positioning of the patient and ports is critical to success for renal surgery with the robotic system. Ports are placed with the camera in the umbilicus, the upper port at the midline between the xyphoid and the umbilicus, and the lower port in the midclavicular line in the ipsilateral lower quadrant (see Fig. 1). The degree of angulation of the patient depends on whether the colon will need to be mobilized, which is determined after the camera port has been placed and the operative site visualized. Only in left-sided pyeloplasty has the transmesenteric approach been used; this requires less angulation of the patient.

The performance of each procedure is well described in the laparoscopy literature. Several particular points may be emphasized.

### *Nephrectomy*

In most cases, three ports are adequate for nephrectomy, but occasionally a fourth port for a retractor is helpful or essential, depending on the anatomy. Use of the ureter to lift and retract the kidney to expose the hilum is useful, although if the hilum is seen readily, it should be controlled as early in the procedure as possible. Full mobilization of the kidney before this often will allow the kidney to fall on the hilum and conceal it.

### *Partial nephrectomy*

The precise control provided by the robotic device facilitates the delicate dissection of the polar renal vessels without excessive traction on the remaining vessels. The enhanced visualization is also an asset when separating the two poles. The harmonic scalpel tissue-cutting device has been adapted to the robot, although it is nonarticulating. It is hoped that an articulating version will be developed. Alternatively, the cautery is useful for separating the poles. Care should be taken with

sealing the cut surface of the residual pole and suturing the edges to avoid a leak or urinoma. These have been reported with a small frequency with conventional laparoscopic partial nephrectomies, although the cause is unclear [2]. A leak from the residual pole is a possible, but unlikely cause of this. Suturing the edges as in open surgery is performed readily with the robot.

### *Pyeloplasty*

Pyeloplasty has been performed most extensively with the robotic device; the ability to suture with precision and control is the advantage. The author has found that a hitch-stitch, as initially described by Tan [3] in pediatric pyeloplasty, is useful to maintain exposure of the renal pelvis and anastomotic sight, avoid blood obscuring the anastomosis, and stabilize the tissues during the anastomosis. This is placed before dismembering the UPJ and is sutured to the anterior abdominal wall or passed through the wall and back to control tension from the outside. The latter method is limited by the robotic arms, which can block access to the abdominal wall.

The anastomosis can be interrupted or running suture, and a monofilament is preferred. The interrupted suturing is slow because of the need for cutting the sutures after each tie. It is not advisable to break the sutures intentionally instead of cutting because this may tear the anastomosis. The length of the suture is important, and requires a compromise between efficient handling of the suture, which becomes clumsy if too long, and the need to run a suture along the side of the renal pelvis. A 14- to 16-cm suture works well in most cases, and, if used for interrupted sutures, will permit three to four knots. The free tail of the suture should be kept short to reduce the need for wide spreading of the instruments when the knot is being tied down and to facilitate finding the end. If it is too long, it may adhere to moist surfaces and be difficult to grasp or see.

During most dissection, the instrument is set on fine scaling. This provides a good degree of control, but does not require wide hand movements to achieve a moderate instrument move. During suturing, especially for small children, the ultrafine setting is used to enhance precision and accuracy. Interrupted suturing may be performed, but requires more time because the individual knots must be cut, which requires an instrument change. Running suture is more efficient and equally effective. The posterior aspect of the anastomosis

is performed first, at which point a double-J stent can be placed if desired.

Stenting offers the advantages of not requiring a separate drain and permitting rapid drainage of the kidney. It requires removal, usually between 2 and 4 weeks later with a brief anesthesia. Preplacement of a stent with an extraction string has been described, but the author's experience with more than a few days of a dangling urethral stent has not been good. If a stent is placed intraoperatively, it is accomplished by first passing a 16-gauge angiocatheter through the abdominal wall, just below the ribs and under direct vision. The needle is withdrawn and a 28 or 35 wire is passed through the catheter and guided into the proximal ureter. It then is advanced into the bladder with the stent being passed over it and moved into the ureter and bladder. The wire is withdrawn and the proximal coil positioned in the renal pelvis. Position can be confirmed with blue dye in the bladder, which is seen to reflux up the stent.

The anterior aspect of the anastomosis and the pelvic closure then is completed. The mesentery is closed over the renal pelvis with chromic suture or the bowel is allowed to fall back over the kidney. The area of work is irrigated and any drained urine is aspirated from the lateral gutter or pelvis. Cannulae are withdrawn after the robot is disengaged and the preplaced fascial sutures are tied. Local anesthetic is instilled into the port sites and the skin closed. A Foley catheter is left in the bladder overnight; if the child is taking oral liquids and is comfortable on oral analgesics, he or she may be discharged the next day. Some patients require a second night's stay, but it is not routine. The stent is withdrawn cystoscopically in 2 to 4 weeks. As with any pyeloplasty, an ultrasound is performed 4 weeks after stent removal to assess drainage. Functional imaging is reserved for 6 to 9 months postoperatively, or if the degree of hydronephrosis is increasing or the child is symptomatic.

### *Results of pyeloplasty*

The initial experience with pyeloplasty has been good. With follow-up available on 18 patients, outcomes are shown in Table 1.

The two early failures include one patient in whom a pair of anterior crossing vessels was not detected during the initial operation because it was performed retroperitoneally in a child who presented with acute pain and required preoperative stent placement. The pelvis was decompressed and

Table 1  
Initial experience with robotic pyeloplasty

Characteristic	Outcome
Patients (no.)	
Male	14
Female	8
Laterality	
Right	8
Left	14
Age	
Mean	107 mo
Range	5–228 mo
Exposure	
Retro-colic	15 (1 retro-peritoneal); mean operating time 2.8 hr
Transmesenteric	7; mean operating time 2 hr
Stent	
Stent/nephroureteral	15 (3 nephroureteral); mean operating time 2.8 hr
None	7; mean operating time 2.2 hr
Outcomes	
Follow-up (mean)	
Imaging	6.6 mo
Total	13.8 mo
Evaluable patients	18; 1 long-term follow-up; 3 pending
Satisfactory	17 (94%)
Persisting obstruction	1 (2 early); 1 required reoperation for missed crossing vessel (done retroperitoneally); 1 required 3 mo of nephrostomy drainage after urgent placement for leak and ileus

One bilateral simultaneous pyeloplasty patient (7 yr) not included—satisfactory result.

somewhat indurated, which may have contributed to the lack of recognition of the vessels. He underwent a second pyeloplasty robotically using a transperitoneal approach and the ureter was transposed anterior to the vessels. The second patient developed an acute postoperative leak with ileus and underwent nephrostomy tube placement. The nephrostomy was removed 3 months postoperatively with evidence of adequate drainage.

Operative times have improved and are near that of open surgeries, although they remain longer. This likely will improve, although they may not reach those possible for open surgery. The success rate seems acceptable, although more cases are needed after initial experience has been gained. The subjective benefit of using a robotic device to perform a laparoscopic pyeloplasty is the high quality of the visualization of the anatomy, which

allows precise handling of the tissues, suture placement, and control of the repair. These benefits ultimately should enhance outcomes. The infant undergoing pyeloplasty is not benefited markedly by laparoscopic methods, but the older child and the adolescent will be. With smaller instruments, the difference also may extend to younger patients. Surgical times are shorter for younger patients because of the facility of exposing the renal pelvis.

### Pelvic surgery

The pelvis is a satisfying area of use for the robotic device, particularly for retrovesical procedures. The visualization is excellent and one may perform delicate manipulations behind the bladder with excellent control. Excision of Müllerian remnants, seminal vesical cysts, or any bladder-neck procedure is amenable to these maneuvers. It is often advisable to use the 30° upward scope to perform these procedures. The rectum is decompressed with a preoperative suppository and a rectal tube is placed at the start of the procedure. Exposure of a complex Müllerian structure in a boy with the ring-Y chromosomal abnormality is shown in Fig. 4.

### Bladder surgery

#### Extravesical antireflux surgery

Laparoscopic antireflux surgery was described initially 10 years ago, but never achieved real

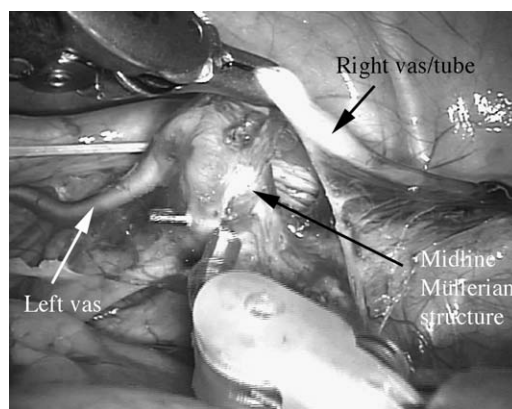


Fig. 4. Laparoscopic appearance of a persistent Müllerian structure in a boy with the ring-Y chromosomal abnormality. The right testis was dysgenetic and the left was intrascrotal, but he had developed recurrent epididymitis.

popularity, presumably because of the difficulty in dissection and suturing. It has been reintroduced slowly in the last 4 years [4], but is still a technical challenge. With the robotic device, it is feasible for most surgeons, and the author's initial results support continued investigation of its value. The approach is to perform an extravesical, transperitoneal Lich-Gregoir procedure. Bilateral extravesical reimplantations have been associated with an increased risk for transient urinary retention [5], although it has been claimed that laparoscopic procedures have less risk [4]. This assertion is not established, and the author's experience suggests that the risk remains. The author's team has therefore expanded its methods to include a transvesical ureteral reimplantation, using the transtrigonal or Cohen method. This idea was presented by Olsen and colleagues [6] using conventional laparoscopy, and explored experimentally.

For unilateral procedures, an extravesical approach is used with the ports placed as shown in Fig. 5. In girls, the ureter can be seen cephalad to the uterus and its orientation determined. The ureter is exposed by incising the peritoneum anterior to the uterus and sweeping the uterine ligament and pedicle posteriorly. The ureter then is seen just outside the bladder, mobilized, and cleared for approximately 4 or 5 cm. Care is taken to avoid too extensive a mobilization. The posterior bladder wall then is cleared and the bladder partially filled.



Fig. 5. Port placement for extravesical ureteral surgery for vesicoureteral reflux.

A detrusor incision is made and taken to the level of the mucosa for approximately 2.5 to 3 cm. It is best to peel the detrusor off the mucosa laterally to facilitate wrapping the ureter (Fig. 6). A Y-shaped mobilization around the hiatus of the ureter is performed, but not circumferentially [7]. The detrusor then is sutured over the ureter using 3-0 or 4-0 Polydioxanone or Vicryl suture. A hitch stitch drawing the bladder upward may be used to aid in exposure. The muscle may be brought around the ureter working either from distal to proximal or the reverse. Working from distal to proximal permits clear visualization of all structures, but requires passing the needle under the ureter during the closure. A bladder catheter is left in place overnight in most children, although older children may require longer hospitalization.

Table 2 shows the outcomes of the author's initial experience with extravesical antireflux surgery using robotic assistance. Two patients have had some degree of voiding difficulty, one of whom underwent a bilateral procedure. One child undergoing a unilateral nephrectomy and contralateral extravesical ureteroplasty developed a rising creatinine and hydronephrosis, necessitating placement of a ureteral stent. It is recommended based on this case (of four combined nephrectomy-reimplants) that a stent be placed for solitary kidneys. This child had no hydronephrosis and a normal creatinine 1 month after stent removal. Reflux has persisted in two children, raising the question of whether the laparoscopic method can provide an adequate tunnel. This is a lower success rate than that of open extravesical ureteroplasty, which should have a nearly 100% success rate. This may

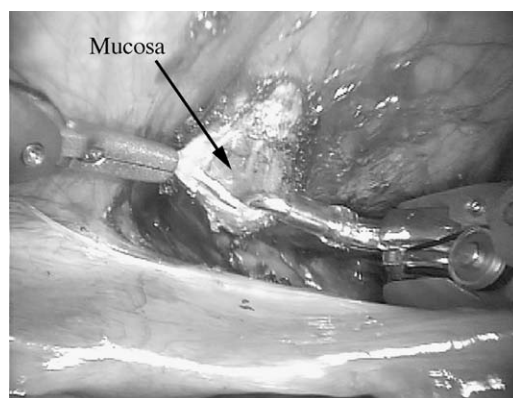


Fig. 6. Creation of the detrusor tunnel by incising the detrusor and exposing the mucosa of the bladder and peeling back the muscular detrusor.

Table 2  
Initial experience with robot-assisted extravesical antireflux surgery

Characteristic	Unilateral	Bilateral	With contralateral nephrectomy
Patients			
Female	15	3	1
Male	2	0	3
Laterality			
Right	9	—	0
Left	8	—	4
Age (mean)	74 mo	108 mo	19 mo
Range	4.6–140 mo	69–130 mo	7–37 mo
Reflux grade (mean)	2.9	2.3	2.9
Operative times	2.0 hr	3.5 hr	NA
Range	1.3–3.5 hr	3.4–3.6 hr	
Outcomes			
Follow-up (mean)	5.7 mo	8.7 mo	7 mo
Evaluable patients	17	3	4
Satisfactory	15	3	3
Persisting reflux	2 low grade; being observed for likely resolution		1 low grade; being observed for likely resolution
Other complications	1 bladder leak responded to drainage	1 bladder leak and voiding difficulty (transient)	1 transient obstruction; stent placed for 3 wk

Abbreviation: NA, not applicable.

reflect being early in the learning curve, and care will need to be taken to assess tunnel length and quality of the tissues making the tunnel.

#### *Transvesical antireflux surgery*

Intravesical ureteral reimplantation is performed in a manner identical to the Cohen trans-trigonal reimplantation. The major challenge is gaining and maintaining access to the bladder. The puncture sites must be sealed well to maintain an adequate operative field and avoid leakage of carbon dioxide into the retroperitoneum. The author's team has found it successful to place the port sites just above the level of a normal Pfannenstiel incision and start with the bladder filled with saline.

Blunt dissection in the midline is used to expose the bladder dome and sutures are placed in this to lift and ultimately to hold the bladder wall up. The camera cannula then is placed into the bladder. If the saline filling is maintained, the two working cannulae are placed more easily. The carbon dioxide then is used to fill the bladder and displace the saline. The bladder puncture sites for the working ports are held securely with sutures,

which then are used to close the bladder at the completion of the procedure. This is more difficult in older patients in whom the subcutaneous tissues are more generous.

Once in position, the procedure is as with an open reimplant. A feeding tube is placed in the urethra to suction any urine or blood and is positioned by the working instruments, with suction applied intermittently. A 5- or 6-cm segment of feeding tube is placed into the ureters to aid in ureteral dissection. One suture is placed in the inferior aspect of the ureter for traction during dissection. Developing the tunnels is efficient because the scissors may be angled completely parallel to the trigone because of the articulation of the robotic instruments. This is not feasible even with open surgery (Fig. 7). The ureters are brought through the tunnels and sutured into position using 4-0 or 5-0 monocril or chromic suture. The path of the ureter is checked after completion of the anastomosis using a feeding tube to ensure there is no obvious obstruction or twisting of the ureter. The port sites in the bladder are closed using the preplaced bladder wall sutures, which are now tied. Fascial and skin stitches are placed to close the port-site defects.



Fig. 7. Creation of the submucosal tunnel to perform a transvesical robotically assisted transtrigonal reimplantation (Cohen). The articulating ability of the robotic instruments facilitates this step.

Postoperatively, the child stays in hospital until he or she is able to maintain adequate hydration and oral pain control. This is usually 1 to 2 days, but has been longer. An ultrasound is obtained 1 month postoperatively and a voiding cystography in 3 months.

Few patients have undergone this technique, and the challenge of accessing the bladder and closing the puncture sites remains unresolved. In one patient who had a thicker abdominal wall, one port site could not be closed. A bladder catheter was left in place 2 days longer and she voided comfortably, but subsequently developed a leak necessitating replacement of the catheter for 1 week further. Her ultimate outcome was successful. Whether specialized instruments will permit an effective and efficient solution to this issue is unclear.

A broader question is whether laparoscopic techniques using robotic assistance will be advantageous over open methods. The scar for open reimplantation is low and nearly invisible after several years, the recovery is quick, and the success rate is extremely high. Subjectively, patients seem to recover more fully more quickly, but this is difficult to prove objectively. Parents with experience with both procedures prefer the laparoscopic approach, but that too is subjective. The reduction in tissue trauma and the ability to manipulate the tissue accurately and suture intravesically argue in favor of pursuing further robotic development, but it must be recognized that this is not a finished

product and further evolution and evaluation are needed.

A few more complex reconstructive procedures have been performed using the robotic device, including creation of a continent catheterizable stoma using the Mitrofanoff principle with appendix [8]. The appendix is harvested readily and can be sutured into the bladder in a detrusor tunnel as with an extravesical reimplantation. This limits the need for a large midline incisions, yet provides excellent exposure and surgical manipulation.

## Summary

Robotically assisted laparoscopic surgery likely will be a part of pediatric urologic surgery [9]. It will look different than it does now because of technologic and procedural innovations. The inherent value of precise visualization, tissue handling, and reconstruction, coupled with the reduced morbidity of laparoscopic surgery, suggests the potential value of these technologies and methods. Although there is much development to be done, the early results are encouraging [1]. Pediatric urologists specifically, and pediatric surgical practitioners in general, must be involved in the evolution of these techniques and devices, to prevent having to adapt adult surgery-oriented systems to pediatric patients. Pediatric urologists need to be involved in this development actively to guide its course.

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## Robotic adrenalectomy

Alireza Moinzadeh, MD, Inderbir S. Gill, MD, MCh<sup>\*</sup>

*Section of Laparoscopic and Minimally Invasive Surgery, Glickman Urological Institute, Cleveland Clinic Foundation,  
9500 Euclid Avenue, A-100, Cleveland, OH 44195, USA*

Since the first laparoscopic adrenalectomy performed in 1992, laparoscopy has emerged as the criterion standard procedure for surgical treatment of benign adrenal diseases [1]. In the last 5 years, there have been concurrent improvements in the field of robotic surgery. Almost all urologic procedures initially performed laparoscopically have been performed with robotic assistance. This article reviews the current world experience with robot-enhanced adrenalectomy. The initial laboratory experience is summarized, followed by techniques and existing clinical series. Finally, the authors speculate on the future role of robotic adrenalectomy for the treatment of surgical adrenal disease.

### Laboratory experience

With the emergence of robotics in other fields of medicine, its advantages, namely restoration of three-dimensional visualization and six degrees of motion, quickly have become realized [2]. In retrospect, it seems fitting that the natural progression would include testing of the feasibility of robotic surgery in urology. Sung and Gill [3] reported the initial robotic pyeloplasty in the literature. Although this study was interesting in regard to upper urinary tract reconstruction, it more importantly helped establish the foundation for further animal and clinical endeavors in robotic urologic surgery.

Gill and colleagues [4] next compared robotic versus conventional laparoscopic adrenalectomy. In this study, four pigs underwent robotic adrenalectomy using a combination of the AESOP

(Automated Endoscope System for Optimal Positioning, Computer Motion, Goleta, California) and Zeus (Computer Motion) robotic instruments compared with three conventional laparoscopic adrenalectomies. The robot was manipulated completely telerobotically from a separate operating room. An assistant in the operating room provided suction and changed the robotic instrument heads. Total operative time (51 versus 32 minutes) and actual surgical time (38.5 versus 18.7 minutes) were significantly longer in the robotically performed procedures. Nonetheless, the feasibility of the procedure was demonstrated. In addition, an unplanned inferior vena cava injury was repaired successfully and emergently with remote intracorporeal suturing using the robotic device.

### Surgical technique

Multiple authors using the da Vinci robot (Intuitive Surgical, Mountain View, California) have described the technique of remote transperitoneal robot-assisted laparoscopic adrenalectomy. Desai and colleagues [5] performed left- and right-sided adrenalectomy for a 4.5-cm incidentoma and 3-cm pheochromocytoma, respectively, in two patients. Both procedures were performed successfully in 110 and 165 minutes, respectively. The patients were placed in a modified lateral decubitus position (45°–60°). Five ports were used for the right side, whereas four ports were used for the left side. Port position was similar to that used in conventional laparoscopic adrenal surgery at Cleveland Clinic with the ports at least 6 cm apart to prevent intraoperative robotic arm collision (Fig. 1).

The steps of the procedure are essentially identical to those for laparoscopic adrenalectomy

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<sup>\*</sup> Corresponding author.

E-mail address: [gilli@ccf.org](mailto:gilli@ccf.org) (I.S. Gill).

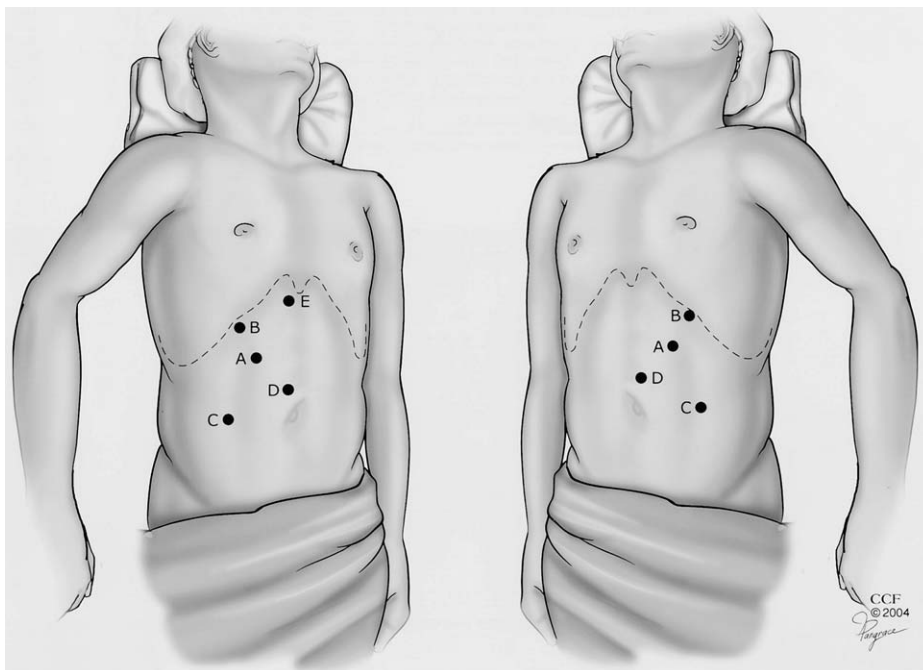


Fig. 1. Port placement for robot-assisted laparoscopic adrenalectomy. The right-sided procedure uses five ports: (A) primary (12-mm) camera port, (B) right (8-mm) and (C) left (8-mm) robotic working ports, (D) assistant (12-mm) port, and (E) liver retraction (5-mm) port. Similarly, the left-sided procedure was performed through four ports; the 5-mm liver retraction port was not used. (Courtesy of The Cleveland Clinic Foundation, Cleveland, OH; with permission.)

[6]. Initial access is obtained by the Veress needle in the subcostal region. Two to three additional trocars are placed in the standard near-triangular fashion. On the right side, the additional port site serves as a self-retaining retractor, pushing the liver in a cephalad direction. The colon is reflected medially along the white line of Toldt. Care is taken to identify the duodenum, which is reflected medially until the vena cava edge is visualized. On the left side, the splenorenal attachments are divided to increase the working space between the upper pole of the kidney and adrenal gland. The tail of the pancreas is identified and pushed medially. The adrenal vein is dissected and ligated with clips placed by the onsite assistant. The onsite assistant also provides suction and aids in retraction. Once the adrenal gland is dissected fully, the specimen is placed in an Endocatch bag and removed through a small extension of one of the port sites.

### Current world experience

Various institutions have published their experiences with robot-assisted adrenalectomy,

although in small numbers (Table 1) [4,5,7–10]. These cases represent the respective institutions' first experiences with robotic adrenalectomy. Beninca and colleagues [9] recently compared the outcomes of nine robotic adrenalectomy cases with those of nine contemporary conventional laparoscopic adrenalectomies. Four of nine (44%) of the robotic cases had to be converted to conventional laparoscopy because of "technical difficulties." Operative times for the robotic cases were longer, with a mean time of 133 minutes (range 104–181 minutes) compared with 82 minutes (range 55–120 minutes). Time to discharge was the same in both groups at 5.7 days. The authors noted that the increased operative time and costs for the robot increased the overall cost. Because the outcomes with conventional laparoscopy were not different, they concluded that robotic adrenalectomy had no significant advantage over conventional laparoscopic adrenalectomy.

In the largest comparison to date, Brunaud and colleagues [10] compared 14 consecutive standard laparoscopic adrenalectomies and 14 consecutive robotic adrenalectomies at one institution. They similarly found that mean

Table 1  
Published series including robotic adrenalectomy

Study	Year	No of robot-assisted adrenalectomy patients	Comment
Horgan and Vanuno [13]	2001	1	First reported case; part of a larger series of 33 other robotic procedures (da Vinci), including gastric bypass, myotomies for achalasia, donor nephrectomy, and gastrojejunostomy. No description of the adrenalectomy technique is given.
Bentas and colleagues [7]	2002	4	Detailed description of transperitoneal robotic telepresent adrenalectomy using da Vinci surgical system. Left and right sides performed. Feasibility demonstrated in pheochromocytoma, adenoma, and adrenal metastasis.
Desai and colleagues [5]	2002	2	Detailed description of transperitoneal robotic telepresent adrenalectomy using da Vinci surgical system. Left and right side performed. Feasibility demonstrated in pheochromocytoma and adenoma.
Young and colleagues [8]	2002	1	Detailed description of transperitoneal robotic assisted (da Vinci) adrenalectomy for an adenoma.
Beninca and colleagues [9]	2003	9	Robotic adrenalectomy using the da Vinci robot. Adrenalectomy cases part of a larger presented series including robotic Nissen Funduplications, myotomies, and cholecystectomy. Authors compared time, cost, and results to conventional laparoscopy group. Four of nine robotic adrenalectomies were converted to open procedure.
Brunaud and colleagues [10]	2003	14	Comparison of 14 robotic to 14 conventional laparoscopic adrenalectomies using the da Vinci robot.

operating time for the robotic procedure was longer than conventional laparoscopy (111 versus 83 minutes,  $P = .057$ ). Operative time decreased to an average of 98 minutes in the last seven robotic patients, attesting to the learning curve. Conversion to open surgery was required in one patient in each group because of bleeding in one case, and difficulty in progression during a case with polycystic kidney disease. There was no difference in terms of complications, length of hospital stay (6.9 versus 6.7 days), and time to return to work (10.3 versus 8.6 days). The authors concluded that no objective benefit of robotic adrenalectomy could be found relative to conventional laparoscopy.

### Future direction

Does robot-assisted laparoscopic adrenalectomy have an advantage over the conventional laparoscopic procedure? The authors have outlined the limited objective data regarding this question. Based on the two series available

[9,10], the authors believe the answer is “no.” Current robotic outcomes do not compare with current laparoscopic outcomes or needlescopic outcomes with regard to operative efficiency, hospital stay, financial implications, or cosmetic results. For example, pure laparoscopic adrenalectomy can be performed efficiently (even on an out-patient basis) in select patients and has financial advantages [11]. Needlescopic adrenalectomy may decrease morbidity further while enhancing cosmesis [12]. Robotic adrenalectomy falls short on these counts.

The purported advantages of the robotic surgical system are the six degrees of motion, the three-dimensional vision afforded by the dual lens scope, and movement-scaling capability. These three attributes are valuable in assisting in intracorporeal microsuturing in reconstructive procedures. Adrenalectomy is an extirpative procedure relying mainly on the knowledge of topographic anatomy. With adequate anatomic familiarity and pure laparoscopic expertise, little may be added by the introduction of robotics, notwithstanding the future applications of telepresent surgery.

## Summary

The use of robotics in surgery is an emerging field. Robot-assisted laparoscopic adrenalectomy has been performed in small numbers worldwide. Advantages of robotic assistance over conventional laparoscopy are not acknowledged. Improvement in robotic technology, including addition of tactile feedback, miniaturization of end-effectors, reduced cost, and advances in remote surgery telecommunication technology are awaited.

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# Pelvic floor reconstruction: state-of-the-art and beyond

Nicole B. Fleischmann, MD, Victor W. Nitti, MD\*

*Department of Urology, New York University School of Medicine, 150 East 32nd Street, New York, NY, 10016, USA*

The use of robotic technology to guide surgeons through the laparoscopic repair of pelvic-floor defects is virtually uncharted territory in the field of urology. The laparoscopic approach to these problems has been limited, partly because of the success and ease of the vaginal repair and partly because of the learning curve required to perform laparoscopic procedures. This article therefore does not review the literature on robot-assisted repairs of the pelvic floor, but instead considers the anatomy of pelvic support and the conditions associated with defects in support. Current surgical techniques for restoring pelvic-floor function and anatomy are discussed, as well as future possibilities that technology will provide urologists who wish to broaden their treatment approaches for prolapse repair.

## Overview of pelvic floor defects: anatomy of pelvic support

Any approach to surgical reconstruction of pelvic-floor defects requires a thorough understanding of the anatomy of pelvic support. As a matter of semantics, many experts prefer to refer to pelvic-support defects in a “compartmentalized” fashion. Urologists describe defects such as cystocele, rectocele, and enterocele. More appropriately, the vagina can be divided into anterior, apical, and posterior compartments. A defect in anterior support preferably is described as “anterior prolapse” as opposed to “cystocele” because one cannot be certain of the components of the prolapse based on physical examination alone.

The same holds true for apical and posterior prolapse.

In general, pelvic support depends on the fascia and muscles that surround the pelvic organs and the bony pelvis, which provides the framework for their attachment. The fascial investment is a continuous body of connective tissue from the pubic symphysis to the pelvic sidewall and sacrum that envelops the pelvic viscera and levator muscles. The levator plate is comprised of a group of muscles upon which the pelvic organs rest. This muscle group includes the pubococcygeus, iliococcygeus, puborectalis, and coccygeus muscles. The levator muscles and their associated fascial coverings attach anteriorly to the pubic bones, laterally to the arcus tendineus (the thick condensation of the obturator fascia that extends from the ischial spine to the pubis) and posteriorly to the sacrum and coccyx. The urethra, rectum, and vagina traverse through an opening in the plate known as the levator hiatus.

The importance of the pelvic musculature in supporting the pelvic floor cannot be overemphasized. Most surgical descriptions of prolapse and prolapse repair talk in terms of fascial attachments, but strong, intact, well-innervated muscles are most critical to pelvic support. When pelvic-floor muscles function properly, there is little stress on the fascial attachments. When muscles fail, as a result of trauma or nerve injury, the fascial attachments must assume the bulk of the support role, for which they are not designed.

The pelvic organs are suspended over the pelvic floor by the endopelvic fascia (EPF) and the levator ani muscles. Delancey [1] described three levels of vaginal support (Fig. 1). The upper vagina, Level I, is supported by the EPF that suspends the vagina to the pelvic sidewall in that region, containing the cardinal and uterosacral

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\* Corresponding author.

E-mail address: [victor.nitti@med.nyu.edu](mailto:victor.nitti@med.nyu.edu)  
(V.W. Nitti).

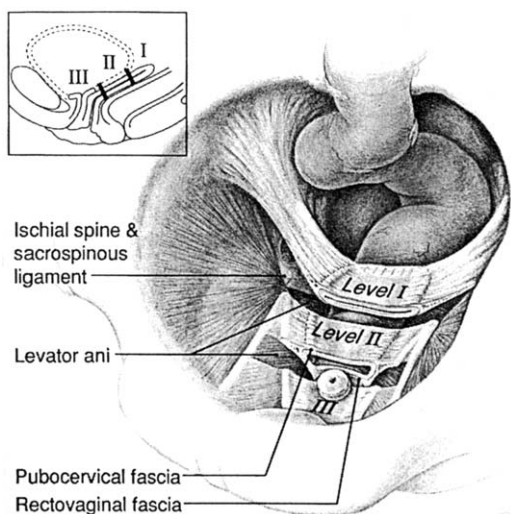


Fig. 1. Levels of pelvic organ support as described by Delancey. In Level I, the paracolpium suspends the vagina from the lateral pelvic walls. Fibers from Level I extend vertically and posteriorly toward the sacrum. In Level II, the vagina is attached to the arcus tendineus fasciae pelvis and support fascia of the levator ani. (From DeLancey JO. Anatomy and biomechanics of genital prolapse. Clin Obstet Gynecol 1993;36:897–909; with permission.)

ligaments that support the uterus, cervix, and upper vagina. The cardinal ligaments, which primarily support the cervix, also support the bladder base as it fuses with the EPF in that region, known as the pubocervical fascia. In cases of uterine prolapse, the cardinal and uterosacral ligaments can be lax, displacing the pubocervical fascia laterally. This also predisposes to cystocele formation. Similarly, apical prolapse (including apical cystocele and enterocele) can occur after hysterectomy as support of the vaginal apex breaks down.

At the level of the midvagina (Level II), the EPF attaches to the vagina more laterally to the arcus tendineus, and stretches it transversely between the bladder and rectum. At the bladder and urethra, the EPF splits into two sheaths that envelop the abdominal and vaginal aspects of these structures. Anteriorly, the EPF forms the pubourethral ligament, which is a pair of dense connective tissue bands arising from the vaginal wall and periurethral tissue and attaching to the undersurface of the symphysis pubis [2,3]. The support of the anterior vaginal compartment (bladder and urethra) depends on the integrity of the EPF and its attachments to the pelvic sidewall at the arcus tendineus (Fig. 2) [2].

Breaks in the integrity of these structures produce defects that result in anterior compartment prolapse, particularly central and lateral defect cystoceles (Fig. 3) and urethral hypermobility that can lead to stress urinary incontinence [4]. A central defect occurs when there is attenuation or a tear in the EPF between the bladder and vaginal wall. A lateral defect occurs when the EPF separates from its sidewall attachment at the arcus tendineus [5]. Lateral defects are thought to be caused by true separation of the EPF at this area, and not attenuation [6]. Defects may be unilateral or bilateral. Isolated lateral defects are fairly common, whereas isolated central defects comprise less than 10% of cystoceles [7]. Combinations of central, lateral, and apical (from Level-I support) fascial defects are common, especially in larger symptomatic cystoceles. The authors believe that apical defects resulting from a breakdown in Level-I support are underestimated in cases of large cystoceles. A rectocele is formed by disruption of the fascia of rectovaginal septum at the level of the midvagina.

The distal vagina, Level III, is fixed securely by direct attachment to adjacent structures. The perineal body is the central point of attachment for the perineal muscles and fascia, providing an anchor of support for the external sphincter, the superficial transverse perineal muscles, the levator ani muscles, and the posterior portion of the perineal membrane and the rectovaginal septum. The main function of Level-III support is to maintain the size of the vaginal outlet, preventing any Level-I or -II defects from emerging beyond the levator plate and urogenital hiatus, resulting in total vaginal eversion [8]. When there is a disruption in Level-III support, a perineal rectocele is formed, which has different clinical and surgical implications from a Level-II rectocele. In the latter, there is a disruption in the integrity of the rectovaginal septum, allowing the rectum to herniate through the posterior vaginal wall. In the Level-III rectocele, there is a complete separation of the perineal body from the rectovaginal septum. The posterior vaginal prolapse is often a combination of posterior Level-II and Level-III defects [9].

### Surgical repair of pelvic floor defects

The anatomy of pelvic support includes muscular and fascial contributions. Although the muscular contribution may be more important,

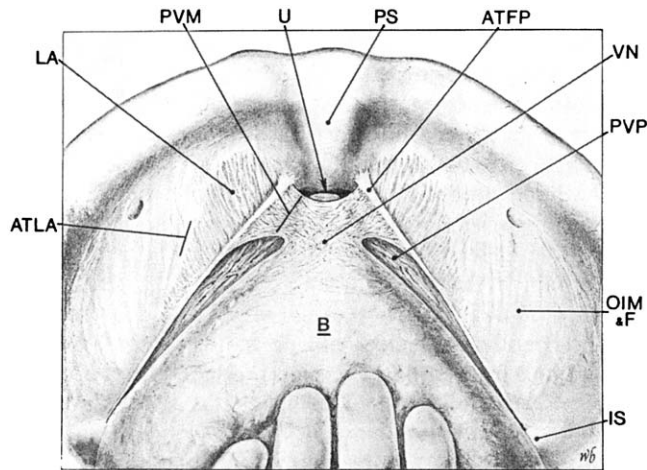


Fig. 2. Retropubic view of bladder neck and urethral support drawn from cadaver dissections according to Delancey. The pubovesical muscle (PVM) goes from the vesical neck (VN) to the arcus tendineus fasciae pelvis (ATFP) and runs over the paraurethral vascular plexus (PVP). ATLA, arcus tendineus levator ani; B, bladder; IS, ischial spine; LA, levator ani muscles; OIM&F, obturator internus muscle and fascia; PS, pubic symphysis; U, urethra. (From DeLancey JO. Pubovesical ligament: a separate structure from the urethral supports ("pubourethral ligaments"). *Neurourology* 1989;8:53–61, copyright Wiley-Liss, Inc; with permission.)

the fascial component typically is "fixed" in prolapse repair. Because defective muscle is not amenable to surgical reconstruction to restore its strength, one must rely on fascial support reconstruction. The goals of surgical correction of pelvic floor defects are to restore anatomy and function of the vagina and pelvic organs. It is important to consider the anatomic positions of the pelvic organs as well as vaginal depth so as not to compromise sexual function. Numerous techniques have been proposed, demonstrating the challenge surgeons face to accomplish this task properly. There are three primary approaches to reconstructive surgery: vaginal, abdominal, and laparoscopic. This article describes several techniques that demonstrate various principles of restoring pelvic support.

#### *Vaginal approach*

Transvaginal operations are used often because they are relatively easy to perform and have decreased morbidity and hospital stay compared with open transabdominal techniques. They also allow the surgeon to repair all defects simultaneously. The criterion standard transvaginal procedure for stress incontinence is the autologous fascia pubovaginal sling [10]. Over the years, the sling has undergone many modifications from biologic and synthetic materials, bone-anchored

slings, and, more recently, the midurethral polypropylene sling placed from retropubic and obturator approaches. The sling is an appropriate procedure for urinary incontinence secondary to urethral hypermobility or intrinsic sphincter deficiency. Slings are thought to work by restoring the support of the urethra either at the bladder neck or at the midurethra during increases in intrabdominal pressure, preventing urine leak. It is combined easily with transvaginal prolapse repair, and is performed best following the repair of the anterior and apical defect.

Vaginal repair of a cystocele includes variations of anterior colporrhaphy for central defects and the vaginal paravaginal repair for lateral defects. Both repairs are safe and effective in the correction of the simple cystocele [11,12]. Anterior colporrhaphy involves plication of attenuated pubocervical fascia across the midline, usually with absorbable sutures. The use of absorbable mesh to reduce the bladder before plication of the pubocervical fascia also has been described. Sand and colleagues [13], in a randomized trial, showed a significant reduction in recurrence rates when polyglycolic acid mesh was used. Several authors recently have described the use of permanent mesh and biologic materials to replace or bolster the pubocervical fascial defect repair [14–17]. Such materials can be secured to the levator or obturator fascia laterally on each side. Although

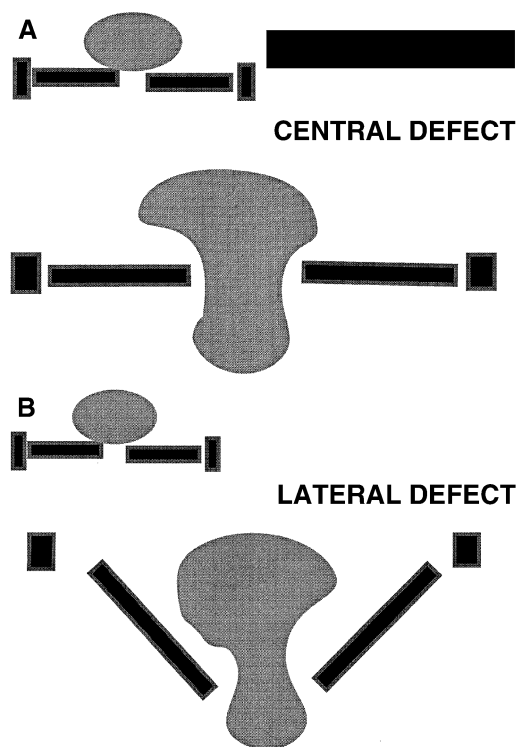


Fig. 3. (A) Central defect cystocele. Note the break in the pubocervical fascia causing central herniation. Inset shows normal support. (B) Lateral defect cystocele. Note the laxity or break in the attachment of the endopelvic fascia to the arcus tendineus fasciae. (From Chopra A, Raz S, Stothers L. Pathogenesis of cystoceles-anterior colporrhaphy. In: Raz S, editor. Female urology. Philadelphia: WB Saunders Company; 1996. p. 338–343; with permission.)

early results are encouraging, no prospective, randomized trials have evaluated these various techniques and materials. In addition, the use of synthetic mesh for primary cystocele repair remains controversial because of the unproven advantage of using mesh and the possibility of mesh erosion in up to 9% of cases [18]. Lateral defect repair by paravaginal repair, performed through a vaginal approach, is technically challenging, but allows one also to perform a central defect repair in cases of combined defects. After exposure of the arcus tendineus, permanent sutures are placed through it (or the obturator fascia) and the pubocervical fascia, plus the full thickness of vaginal wall, excluding the epithelium [19]. The procedure may be combined with graft interposition from arcus to arcus.

Posterior Level-II and -III defects are repaired easily through the transvaginal approach. The traditional posterior colporrhaphy reinforces the rectovaginal septum with several absorbable mid-line sutures through the perirectal fascia and levator muscles. It is usually necessary to perform perineorrhaphy at the same time, which reattaches the rectovaginal septum to the repaired perineal body. More recently, several authors have advocated the site-specific rectocele repair in which the surgeon places a finger in the rectum and then localizes and repairs specific defects rather than performing a midline plication. Site-specific repairs are effective and reduce the risk for post-operative dyspareunia [20,21].

Transvaginal suspension procedures for an apical defect involve fixing the vaginal cuff to the strong pelvic ligaments: the sacrospinous, uterosacral, or iliococcygeus fascia. A vault suspension usually is performed along with a procedure to obliterate the cul-de-sac (culdoplasty) to prevent or treat an associated enterocele. This can be done after or in conjunction with a vaginal hysterectomy. The sacrospinous ligament fixation (SSLF) (Fig. 4) popularized by Randall and Nichols [22] can be bilateral or unilateral and usually is done through a posterior approach [23]. Recurrence rates are variable (7%–50%) and depend on the criteria used (anatomic versus subjective) [24–27]. Recurrences tend to occur more in the anterior than the apical compartment. The addition of a site-specific paravaginal repair for associated lateral defects has not decreased the rate of recurrent anterior prolapse associated with SSLF [28].

Some authors have criticized SSLF for distorting the vaginal axis and predisposing the patient to recurrent anterior compartment prolapse. Other authors have reported additional complications of hemorrhage, pudendal and sciatic nerve injury, and severe, often debilitating buttock pain requiring reoperation and suture removal [29–31]. With the development of suture-capturing devices to aid in more precise needle placement, modifications to the posterior approach, and addition of mesh reinforcement in the repair, improvements in these areas may continue [32–34]. It is the authors' impression that modifications in technique using mesh have decreased operative time with comparable initial results, but long-term results have yet to be reported.

Citing high recurrence rates with SSLF as a result of breakdown of transverse or apical support, Shull and colleagues [35] described

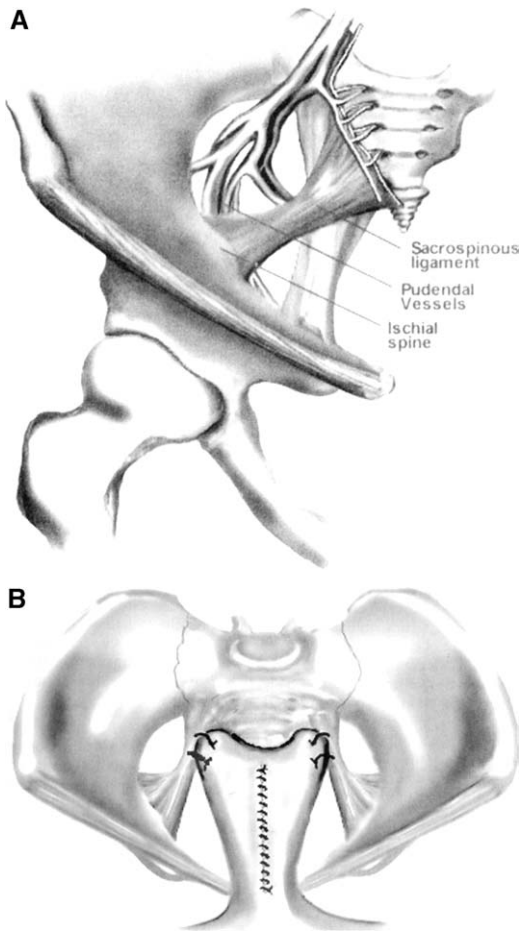


Fig. 4. (A) The sacrospinous ligament, which is covered by the coccygeus muscle, stretches from the ischial spine to the sacrum. The pudendal neurovascular structures pass beneath the sacrospinous ligament at the ischial spine, and sacral neurovascular structures are present at its medial attachment to the sacrum. (B) The final appearance of the anterior approach bilateral sacrospinous ligament. (From Cespedes RD. Anterior approach bilateral sacrospinous ligament fixation for vaginal vault prolapse. *Urology* 2000;56(6 Suppl 1):70–5; with permission.)

a transvaginal uterosacral ligament fixation (USLF) approach (Fig. 5). This technique reduced anterior recurrence rates dramatically when compared with SSLF. In their study of over 300 women who underwent USLF, there was an 87% anatomic success rate and a markedly reduced recurrence of 7%. A large study by Karram and colleagues [36] had similar results. In cases where the uterosacral ligaments cannot be identified, an iliococcygeus fascia fixation can be performed.

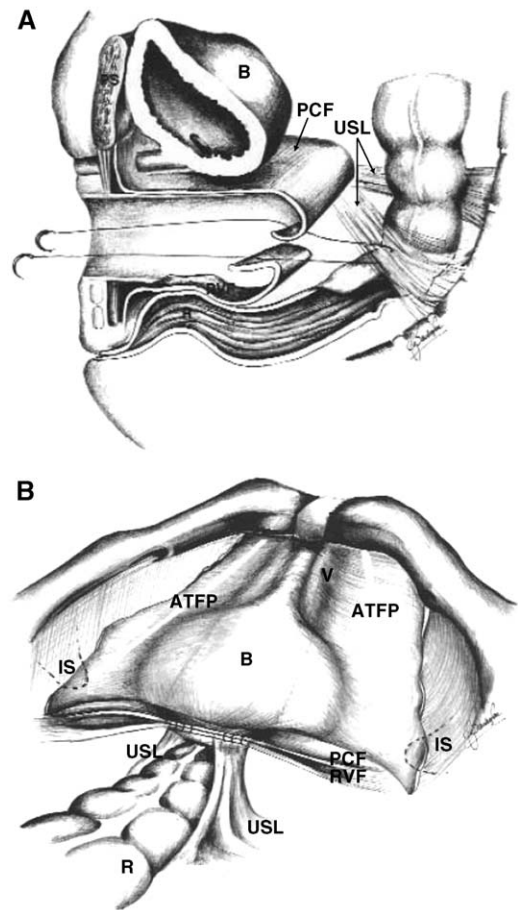


Fig. 5. (A) Sagittal view of suspensory suture in left uterosacral ligament (USL) with one arm through pubocervical fascia (PCF) and one arm through rectovaginal fascia (RVF). PS, pubic symphysis; B, bladder. (B) Abdominal view of completed repair. ATFP, arcus tendineus fasciae pelvis; IS, ischial spine. (From Shull BL, Bachofen C, Coates KW, Kuehl TJ. A transvaginal approach to repair of apical and other associated sites of pelvic organ prolapse with uterosacral ligaments. *Am J Obstet Gynecol* 2000;6:1365–73; with permission.)

Long-term results are needed to determine the utility of these procedures over the SSLF. The authors believe, however, that future techniques to repair apical and anterior prolapse should consider the apical or transverse support of the bladder as well as the vagina.

#### Abdominal approach

The paravaginal repair is the most popular abdominal operation for lateral defect cystocele.

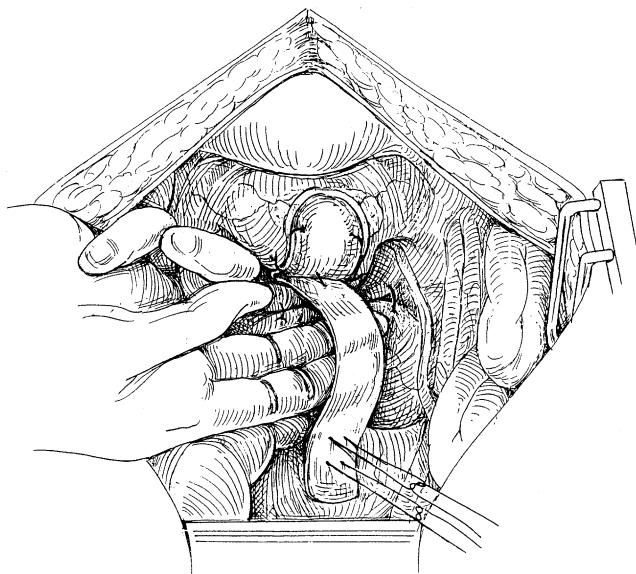


Fig. 6. Abdominal sacral colpopexy. Y-shaped mesh attached to vaginal cuff and sacral promontory with nonabsorbable sutures. (From Winters JC, Cespedes RD, Vanlangendonck R. Abdominal sacral colpopexy and abdominal enterocele repair in the management of vaginal vault prolapse. *Urology* 2000;56(6 Suppl 1):55–63; with permission.)

The procedure, which restores the lateral attachment of the vagina to the pelvic sidewall, was proposed originally as a site-specific alternative to the anterior colporrhaphy. The paravaginal fascia is secured to the arcus tendineus from the ischial spine to the symphysis pubis [37]. Although the paravaginal repair is an excellent operation for lateral defect cystocele, it is not recommended for the treatment of stress incontinence. As an incontinence procedure, the paravaginal defect repair falls short of Burch colposuspension, the criterion standard procedure for incontinence [38]. Paravaginal repair can be combined easily with a Burch procedure simply by placing a set of sutures through Cooper's ligament. The authors recommend this approach in cases of stress incontinence associated with urethral hypermobility. A disadvantage of the paravaginal repair compared with the anterior colporrhaphy is that it does not address a central defect.

Vaginal vault suspensions through the abdominal route for the repair of apical prolapse have the highest reported long-term success rates. The point of fixation can be the sacral promontory or uterosacral ligaments (most commonly at the time of hysterectomy). Abdominal sacral colpopexy can be performed through a small Pfannenstiel incision or lower midline incision. Here, the

vaginal apex is fixed to the sacral promontory with graft interposition (Fig. 6) [39]. Usually synthetics are used, but autologous fascia and biologic materials have been used also. A Y-shaped graft usually is used, with each wing of the Y sutured to the vaginal wall anteriorly or posteriorly. The base is fixed to the periosteum of the sacral promontory. Permanent suture is used at all fixation points and the graft is retroperitonealized. Usually, a Halban or McCall culdoplasty is performed to obliterate the cul-de-sac and prevent future enterocele.

Associated procedures for stress incontinence or lateral defects can be done as needed (eg, paravaginal repair or Burch procedure). Cundiff and colleagues [40] described a procedure in which abdominal sacral colpopexy was combined with a posterior repair for the treatment of rectocele. They dissected the rectovaginal space to the perineal body and attached the nonabsorbable mesh to the distal rectovaginal septum and perineal body. The abdominal sacral colpopexy has consistent long-term follow-up cure rates of 90% to 99% [41–43]. An additional benefit of the operation is that it is not necessary to excise part of the vaginal wall, which preserves vaginal length and reduces the risk for vaginal mesh erosion, which occurs in approximately 5% of cases. The

abdominal approach has the disadvantage of increased morbidity and hospitalization compared with the transvaginal approach, however. For many surgeons, this route is ideal in younger patients to ensure future sexual function and in patients who have failed previous transvaginal prolapse repair.

The debate over the best approach to the apical defect is unresolved. Two prospective randomized studies have been performed. Benson and colleagues [44] randomized 88 women with uterine or vaginal vault prolapse to two groups: (1) bilateral sacrospinous fixation with vaginal paravaginal repair or (2) abdominal sacrocolpopexy with paravaginal repair. Associated procedures (eg, anti-incontinence) were performed as necessary. At a mean 2.5 years of follow-up, surgical outcome was optimal in 29% versus 58%, satisfactory in 33% versus 26%, and unsatisfactory in 33% versus 16% of the vaginal group and abdominal group, respectively ( $P < .05$ ), demonstrating the greater efficacy of the abdominal approach. Recently, Mahrer and colleagues [45] reported on 95 patients who were randomized to abdominal and vaginal repair. At 2 years' follow-up, there was no statistical difference in cure rates between the groups. Subjective success was 94% in the abdominal group and 91% in the vaginal group and objective success was 76% in the abdominal group and 69% in the vaginal group. The only statistical difference was longer operating time and longer return to daily activities in the abdominal group.

### *Laparoscopic approach*

The appeal of the laparoscopic approach to pelvic-floor defects lies in the ability to perform a site-specific repair with excellent visualization but without the morbidity of an abdominal incision. Laparoscopy has been applied to all areas of pelvic surgery, but there are limited reports in the literature regarding clinical outcomes. With respect to prolapse repair and incontinence surgery, laparoscopy has been used mostly for anterior and apical prolapse as well as for incontinence (laparoscopic Burch procedure). Posterior repairs can be preformed by extending repairs to the posterior vaginal wall and perineal body, however.

The laparoscopic Burch colposuspension was first described by Vancaillie and Schuessler in 1991 [46]. There have been numerous variations of the procedure (transperitoneal versus

extraperitoneal), and the addition of mesh reinforcement [47]. Few reports have provided long-term follow-up and no prospective randomized studies have compared outcomes in patients undergoing laparoscopic and open colposuspension. In a small comparative study by Polascik and colleagues [48], the laparoscopic procedure took an average of 1.5 hours longer than the open repair, and patients who underwent the laparoscopic urethropexy required less postoperative analgesia, had a shorter hospitalization, and returned faster to normal activity compared with those who underwent open Burch colposuspension. With the advent of minimally invasive midurethral slings, such as tension-free vaginal tape, that have comparable outcomes to open Burch at 2 years in prospective, randomized trials [49], the utility of the laparoscopic Burch as an isolated procedure for stress incontinence remains unclear.

The laparoscopic paravaginal repair probably has more practical application than the Burch because it can correct significant lateral defect cystocele and can be combined with a Burch procedure (if stress incontinence is present) or laparoscopic colposuspension. The laparoscopic paravaginal repair, with or without a combined laparoscopic Burch, has been performed at some centers with results comparable to that of the open repair [50]. A description of the technique as set out by Miklos and colleagues [51] follows.

Using an umbilical 10-mm access port, the infraumbilical region is cannulated, and three additional ports are placed under direct vision. The bladder is filled in a retrograde fashion and, using a harmonic scalpel, a 3-cm incision is made in the peritoneal reflection above the bladder, entering the space of Retzius. The loose areolar tissue is dissected bluntly and the pubic ramus and bladder neck are identified in the midline with Cooper's ligament and the arcus tendineus fascia pelvis laterally. Any paravaginal defects are repaired first, with the aid of inserting the surgeon's nondominant hand into the vagina to elevate the anterior vaginal wall. A 2-0 nonabsorbable stitch is placed through the pubocervical fascia and the white line at the level of the vaginal apex. Two to four sutures are subsequently placed 1 to 2 cm apart to the level of the urethrovaginal junction and this process is repeated on the contralateral side if bilateral defects exist. A Burch colposuspension, if necessary, can be performed afterwards to reduce the risk for hypersuspension of the urethrovaginal junction.

Laparoscopic paravaginal repair also can be performed with an extraperitoneal approach as described by Saidi and colleagues [52].

The laparoscopic sacral colposuspension for apical defects, first described by Nezhat and colleagues [53], has been performed at multiple centers over the last 10 years. The technique involves the placement of four to five ports in the lower abdominal wall, and a sponge stick in the vagina helps delineate the vaginal apex. Any existing enterocele is repaired at this time, along with a Halban or McCall culdoplasty to obliterate the cul-de-sac. The sacral promontory is identified by lateral retraction of the rectum and tilting the patient to her left. A longitudinal incision is made in the peritoneum overlying the sacrum, taking care not to injure any of the presacral vessels. The incision is carried down to the cul-de-sac and the vaginal apex. A Y- or T-shaped mesh is attached to the pubocervical fascia anteriorly and the rectovaginal fascia posteriorly using 0 nonabsorbable suture, taking care not to penetrate the vaginal mucosa. Alternatively, two pieces of mesh can be used and joined together at the vaginal apex. With minimal tension, the mesh is anchored to the periostium and longitudinal ligament of the sacrum in four rows of 0 nonabsorbable suture. Any excess mesh is excised and the overlying peritoneum is closed with a 2-0 absorbable stitch.

The clinical outcomes of the laparoscopic sacral colpopexy seem to be similar to those of the open approach in the short term, but long-term studies in the literature are few [54]. Cosson and colleagues [55] reported on the short-term complications of their series of 83 patients. Mean operative time decreased from 292 to 180 minutes as the surgeons gained experience. Perioperatively, six patients underwent open conversion as a result of “technical difficulties.” In addition, there was one rectal injury and two bladder injuries, and three patients required reoperation for hematoma or hemorrhage. At 1 year’s follow-up, three patients required reoperation for recurrent prolapse or stress incontinence.

In an effort to minimize the possible complications associated with dissection of the sacral promontory (eg, presacral hemorrhage), the Richardson-Saye laparoscopic uterosacral ligament fixation was developed [56]. This technique involves reapproximation of the rectovaginal and pubocervical fascia at the vaginal apex, and attachment of the repaired apex to the uterosacral ligaments bilaterally. One difficulty with the procedure is that the uterosacral ligaments can be

deficient and difficult to identify after hysterectomy. Long-term data on clinical outcomes as well as comparison to the laparoscopic sacral colpopexy are needed to evaluate the procedure better.

### *Robotic pelvic surgery*

Laparoscopic pelvic surgery is challenging. The true pelvis provides a confining space for laparoscopic suturing and instrument manipulation. Operative times are longer, especially for those who have not had formal laparoscopic training. Ideally, the optimal approach to reconstructing the pelvic floor would combine the superior visualization and decreased morbidity of the laparoscopic approach without the steep learning curve and long operative times. Robot-assisted surgery may help pelvic surgeons who are comfortable with transvaginal or abdominal techniques to perform laparoscopic repairs without compromising their surgical outcomes. Current telerobotic devices provide surgeons with three-dimensional imaging, image magnification, motion scaling, and filtering of physiologic tremor. Robots enhance laparoscopic dexterity by performing difficult laparoscopic tasks, such as intracorporeal suturing, quickly and with excellent precision [57].

The use of the da Vinci robot in men for prostatectomy has been reported extensively [58,59]; many reports have demonstrated the ability of surgeons without advanced laparoscopic skills to perform a robotic prostatectomy [60,61]. In the case of laparoscopic pelvic-floor reconstruction, the most challenging aspect is the intracorporeal suturing during sacral colpopexy, a task that can be simplified by the robot. Pelvic-floor reconstruction using robotics has not been reported widely, although its popularity is increasing.

Di Marco and colleagues [62] described the first report on their preliminary results with robot-assisted laparoscopic prolapse repair. Using a silicone mesh, they performed a sacral colpopexy and culdoplasty in five patients, with concomitant pubovaginal sling in three patients. Standard laparoscopy was used to expose the sacral promontory, and dissection of the vagina from the bladder anteriorly and the rectum posteriorly was facilitated by a customized vaginal retractor. The robot was used to suture the Y-shaped mesh graft to the vagina and sacral promontory. A Halban culdoplasty and retroperitonealization of the mesh completed the procedure. The average operative

time was 3 hours and 42 minutes, the average overnight stay was one night and there were no significant complications. At 4 months follow-up, all patients were cured of their prolapse. It remains to be seen whether, in the long run, robotic pelvic-floor reconstruction will offer a significant advantage over laparoscopic, open, and vaginal approaches.

## Summary

Reconstructive surgery for pelvic-floor dysfunction is challenging and complex. It requires an extensive familiarity with pelvic anatomy and a wide armamentarium of surgical procedures to offer patients with various structural defects. Not every patient is suited for every procedure and the surgeon must be able to individualize the approach. Each technique has indications and benefits: vaginal repairs are relatively simple and cause less morbidity than abdominal repairs, which are generally more durable. Laparoscopic repairs provide excellent visualization with decreased morbidity, but operative times are longer, there is greater cost, and learning curves are steep.

Techniques and principles described for vaginal and abdominal approaches can be applied to laparoscopic and robotic surgery, but comparative outcomes are not available. Robotic assistance with the laparoscopic approach may bring this method to the mainstream by helping surgeons who are not trained formally in laparoscopy to perform advanced skills. Advances in technology and surgical skills will support the application of laparoscopic and robotic approaches, and the development of better synthetic and biologic materials likely will improve vaginal repairs. Future studies will determine the utility of the approach.

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# Robot-assisted vasovasostomy

Caleb Fleming, MD

*Center for Reproductive Medicine, Vattikuti Urology Institute, Department of Urology,  
Henry Ford Medical Center, 6777 West Maple Road, West Bloomfield, MI 48323, USA*

Vasovasostomy and vasoepididymostomy are technically challenging procedures that have changed significantly over the last 20 years to improve success rates and decrease the technical difficulty. The shift from macroscopic to microscopic techniques during the 1980s [1–3] improved success rates steadily, from patencies of 80% and pregnancies of approximately 20% to 30% [1,4,5] using macroscopic techniques to patencies of 90% and pregnancies of 50% to 60% using microscopic techniques [1,2,4]. Results are less for patients who have been obstructed for more than 10 years [3,6,7]. Other proposed technique changes include macroscopic [8], microscopic two-layer [3,9], one-layer and its variations [10–12], microdot [13], stents [14], and oblique techniques [15].

Approximately 3% of patients who have vasectomy come for reversal [1], mostly because of the nearly 50% divorce rate in the United States. Because vasovasostomy is such a technically challenging procedure, it has a significant technical failure rate and a long learning curve. The failure rate is caused in part by long-standing obstruction and its effects on the seminiferous tubules but also by a lack of patency of the anastomosis and scarring at the site of the anastomosis. Failures in patency are believed to be a result of “back-wall-ing” the anastomosis, which is scar formation from inadvertently obliterating the lumen with a poorly placed suture and failing to close the anastomosis in a water-tight fashion [4]. These technical problems result from the difficulty in placing microsutures precisely under magnification because of the normal physiologic tremor that becomes apparent under magnification. Using a robot to place the microsutures will make the procedure easier.

One of the robot’s biggest advantages is the scaling setting, which can be set at normal, fine, or ultrafine. The ultrafine setting has a reduction gear of 5:1, which allows the surgeon to make large, gross movements at the robot console that are reduced to fine movements at the end of the robot arms. This eliminates any normal physiologic tremor on the part of the surgeon.

The 5:1 reduction gear on the ultrafine setting allows a degree of precision beyond that possible with human hands. As vasovasostomy has evolved, the use of magnification has increased the technical precision of the suture placement at the anastomosis. The robot also increases the technical precision of the anastomosis by eliminating the normal physiologic tremor. Kuang and colleagues [16] have used the robot for vasovasostomy in human vasectomy tissue *ex vivo* and reported their results. They found significantly less tremor. Using the robot to improve the manual technical aspect of the anastomosis and the 10× magnification of the robot has increased the technical precision of the anastomosis.

## Technique

Techniques for vasovasostomy have been described well [9,10,13]. The robot-assisted vasovasostomy begins in the same way. A paramedian incision is made and the testis is delivered from the scrotum. This makes using the robot for the anastomosis easier when a large amount of the vas deferens has been removed, but is not mandatory. The author has performed robot-assisted vasovasostomy without delivering the testis, but found it sometimes cumbersome. The site of vasectomy is identified and the proximal and distal ends of the vas deferens are isolated using towel clips and fine hemostats (or the surgeon’s instruments of

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*E-mail address:* cflem1@hfhs.org

choice), taking care not to injure the blood supply further than it was during the vasectomy. The ends of the vas deferens are transected and dilated and fluid from the testicular end of the vas deferens is assessed for sperm or clear fluid.

Once the decision is made to proceed with vasovasostomy the ends are approximated loosely using a vasovasostomy clamp, traction sutures of 5-0 polypropylene, or a 4-0 chromic suture in the perivasaal sheath. When this has been accomplished for both sides, the robot is brought into the operating field. The first assistant remains in position, but the primary surgeon moves to the robot console and the robot is placed where the primary surgeon stood. The author has used the da Vinci Surgical System (Intuitive Surgical, Sunnyvale, California).

The robotic anastomosis starts with loading two microforceps into the robot. The first assistant passes into the operating field sutures of 9-0 nylon on the cards from the suture packages. The card is laid in the operating field. The primary surgeon takes the needle directly from the foam card using the microforceps of the robot. This saves the first assistant from trying to place it with shaking hand directly in the jaws of the robot microforceps. The anastomotic sutures then are placed by whichever technique is preferred. The author prefers placing two or three sutures of 9-0 nylon posteriorly in the muscularis of the vas deferens and then four sutures full thickness through the mucosa and muscularis, tying each suture as it is placed (Fig. 1). As additional sutures become necessary, the needles are passed off the operating field using microwipes or arrow-tip sponges as carriers. The author then places

muscularis sutures between the full thickness sutures in a similar fashion (Fig. 2).

It makes no difference if the primary surgeon prefers a one-layer or two-layer technique, or a modification thereof, nor if the surgeon prefers to tie the sutures at the end or as each suture is placed. The author found it easier to tie the sutures as they were placed because it made keeping track of the ends easier and avoided having the first assistant trying to hand the ends to the robot, but this can be overcome with practice. The third arm of the robot can be loaded with scissors to cut the sutures, but the author believes this adds unnecessarily to the cost.

After performing the microsurgical part of the anastomosis on both sides, the robot is pulled away from the operating table and the anastomosis is covered with perivasaal tissue using 4-0 or 5-0 chromic, and the scrotal wounds are closed in the usual fashion.

The author has performed bilateral robot-assisted vasovasostomy on two patients with excellent patency results and considerable ease. Richard Graham, MD of Richmond, Virginia has performed 20 to 30 robot-assisted vasovasostomies with similar results (personal communication, February 2004). He performs these using 8-0 and 9-0 nylon suture and the da Vinci robot. His experience with the decreased learning curve and ease of precision placement of the suture was identical to the author's. He states that the robot will "level the playing field" for surgeons with modest experience who wish to perform microsurgery and those having more experience. Although many procedures will be necessary to demonstrate a benefit in terms of increased success rates for robot-assisted vasovasostomy,

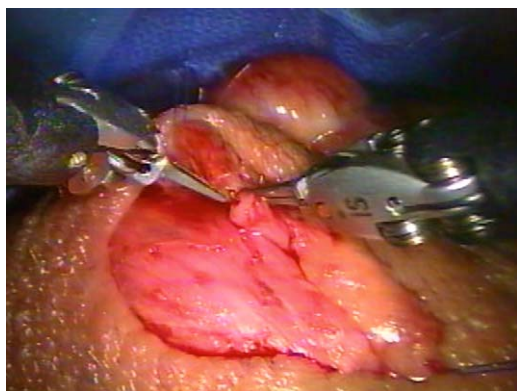


Fig. 1. Placing a suture in the lumen of the vas deferens using the surgical robot.

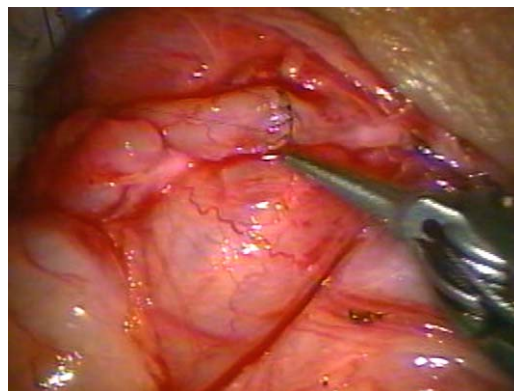


Fig. 2. The completed vasovasostomy anastomosis.

an advantage in using the robot is expected, especially among less-experienced surgeons.

Vasoevididymostomy is more technically challenging than vasovasostomy. Usually vasoevididymostomy is performed using magnification of 16× to 25× with a zoom lens. The da Vinci robot has a 10× lens but is able to “zoom” by moving the camera lens closer. Schiff [17] reported a comparison of standard microsurgical and robotic vasovasostomy and vasoevididymostomy in rats with 10 or more rats in each group. The patency rate was 100% for both robotic groups. Surgical times for the standard and robotic vasoevididymostomy groups were not significantly different. Schiff proposed that what the robot may lack in magnification is compensated for by the increased precision and elimination of the normal physiologic tremor. The first reported cases of robotic vasoevididymostomy in humans should be published soon.

### Training

The learning curve for robot-assisted vasovasostomy is almost nonexistent for experienced microsurgeons. Thirty minutes of dry laboratory using 9-0 suture and a vessel loop or Gore-tex graft would be adequate for most experienced microsurgeons. The most important thing for the surgeon to learn is how tight to pull the suture or how much tension can be applied to the nylon suture before it breaks or is weakened significantly. Tactile feedback is absent when using the robot. The amount of tension applied is learned by the visual cues of the nylon curling.

The usual guidelines for handling tissue and sutures in microsurgery are more important when using the robot [18]. Grasping the suture with the microforceps significantly weakens it and, if pulled hard enough, the suture will break at that point. When drawing the suture tight it is helpful to maintain the grasp on the needle. This is particularly important if the suture is being used for more than one stitch. Experienced microsurgeons will find the transition to using the robot startling. The 5:1 scaling of the robotic arms allows the same precision placement of the sutures at good magnification using relatively large, gross movements at the console of the robot. This seems to make much microsurgical technique and training for handling suture and tissue obsolete for this procedure, but such techniques are still relevant because of the lack of tactile feedback. Ignoring those principles will result in many broken sutures.

### Learning curve

Performing vasovasostomy with the robot and eliminating the normal physiologic tremor has made the procedure less technically challenging and significantly shortened the learning curve. Surgeons can become more proficient, sooner. This has the advantage of training surgeons with fewer cases necessary to become competent. Before using the robot, the author insisted that surgeons learning the microsurgical technique of vasovasostomy participate in a rat microsurgery course and have extensive lab animal microsurgery experience as Yarbrow [3] recommended, as well as perform at least five to eight cases. Since using the robot, the author believes the microsurgery course does not help appreciably, and that only three to five cases are necessary to become reasonably technically proficient. The author recommends that experienced microsurgeons learning to use the robot spend approximately 30 minutes in a “dry lab” practicing suturing with a piece of Gore-tex vascular graft and 9-0 nylon suture. Using 10-0 nylon requires more practice.

### Summary

Robot-assisted vasovasostomy is an attractive alternative to traditional microscopic techniques for several reasons. The normal physiologic tremor is removed and greater ease and precision of suture placement is possible. The training period or learning curve for robot-assisted vasovasostomy is shorter than traditional microscopic techniques. This will allow more surgeons to provide quality technical surgical care for their patients. Additional costs are only a few hundred dollars. As surgical robots become increasingly available and used for a wider variety of procedures, the feasibility of robotic vasovasostomy becomes more realistic and vasoevididymostomy is likely. Although robotic surgery has improved prostate surgery, its contribution to microsurgical technique has the potential for a more profound impact.

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## Establishing a robotics program

William D. Steers, MD, FACS\*, Sam LeBeau, BS,  
Joseph Cardella, MBA, Brant Fulmer, MD

*Department of Urology, University of Virginia, Box 800422, University of Virginia Health System,  
Charlottesville, VA 22908, USA*

The first surgical robot was approved for use in humans in 1994 (AESOP, Computer Motion, Goleta, California). In 1997, the three-armed da Vinci robot (Intuitive Surgical, Sunnyvale, California) was approved for human surgery with additional capabilities allowing expansion of laparoscopic surgery. Since then, the number of hospitals in the United States performing robotic surgery has grown to over 150. Not all of these programs are successful, however, and use of the robot varies.

Establishing a robotics program requires more than transferring a surgical technique to one's hospital or acquiring a new piece of equipment [1]. At the outset, the institution and surgeons should determine whether a program is feasible and identify champions of the endeavor. A multidisciplinary group is ideal and should include surgeons, nurses, and administrators. These champions should assess all components of a robotics program: (1) surgical procedures to be performed, (2) training, (3) personnel, (4) equipment, (5) facilities, (6) operational issues, (7) research, (8) finance, and (9) marketing. This due diligence should begin before the purchase of a robot. The infrastructure needed to establish a robotics program is substantial, and may explain the suboptimal use of robotics at some institutions.

Due diligence requires an assessment of current operating room (OR) facilities, use, and manpower. At academic centers, training strategies for residents and fellows and research applications must be considered. For community and academic centers, the clinical and financial outcomes should

be monitored, the manner of which must be decided at the outset. This monitoring should be followed by a rigorous financial and market analysis. Given the high initial capital and recurring direct and indirect costs, many financially vulnerable hospitals or health systems may choose not to start a program. A timeline should be established that includes OR modification, equipment acquisition, hiring of personnel, and staff training.

Once the program is operational, marketing is a key component with any new procedure or technology because third-party payers often will not reimburse a premium over open surgery, and the only financial justification for increased costs is new patient volume. In this regard, a group from the institution will need to work with third-party payers on reimbursement or the data needed to obtain reimbursement.

This article will explore each of these issues from an academic health system perspective, realizing that geographic and strategic issues vary. The closest analogy to starting a robotics program may be the creation of an open-heart program at a hospital. The authors' department has had the advantage of learning from successful and less successful programs in the United States, as well as from experience over the past 12 months.

### Should an institution start a robotics program?

A risk/benefit analysis will determine whether an institution should pursue a robotics program. Benefits can be achieved for the patient, the surgeon, and the institution. For patients and surgeons, new medical technology generates various degrees of enthusiasm and will attract

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\* Corresponding author.

E-mail address: [wds6t@virginia.edu](mailto:wds6t@virginia.edu) (W.D. Steers).

proponents even before demonstration of improved outcomes. Robotics dangles the promise to lure new patients. It can do this in two ways: (1) attracting new patients specifically for the robot, and (2) publicity for the robot and the institution can attract patients who like the idea of receiving care at a technologically advanced facility, regardless of whether they are treated with the robot.

Level I evidence for improved outcomes based on multiple, prospective, randomized, blinded trials comparing robotic surgery to an open or traditional laparoscopic procedure does not exist. Data crucial for patient and surgeon decision-making to assess benefits often are limited to historical comparisons. Early data suggest that the robotic approach to minimally invasive surgery reduces analgesia requirements, recovery time, blood loss, and other outcome measures compared with open surgery [2–4]. A robotic procedure consistently reduces the learning curve for complex laparoscopic procedures, especially those involving suturing [4,5]. Continued research is needed to support the contention that robotics improves clinical outcomes for certain urologic surgeries or offers an advance over less expensive, nonrobotic laparoscopic surgery.

A benefit for teaching hospitals is the perception by top-quality trainees that an institution with a robotics program is innovative. In 2001, a survey of General Surgery training programs found that up to one quarter of programs planned to include robotics as part of their residency and 57% of responders (1800 surgery residents) indicated very high interest in robotic surgery, yet only 20% had access to a robot [6]. The number of procedures that can be performed by robotic surgery is growing (Box 1).

Another institutional benefit is the potential to become a training site or offer telementoring consistent with institutional educational objectives. The potential for research, including tele-surgery, multimodality imaging, and design of new procedures, may be sufficient reason to establish a program.

These positive aspects must be weighed against significant obstacles and risks. The risk is primarily financial. An initial capital cost of approximately \$1.1 million to \$1.3 million for the robot is a major barrier because recouping this cost is unlikely in the short term. Payers do not provide a premium for robotic or sometimes laparoscopic surgery. Benefactor contributions or leasing often are considered as alternatives to purchasing from a hospital's operating funds. Obtaining

### **Box 1. Procedures performed with robotic surgery**

#### *Cardiac procedures*

Internal mammary artery takedown  
Mitral valve repair  
Epicardial lead placement  
Beating heart totally endoscopic coronary artery bypass (TECAB) (single vessel)  
Arrested heart TECAB (single and multiple vessel)  
Esophagectomy  
Thymectomy

#### *General surgery procedures*

Nissen fundoplication  
Gastric bypass  
Heller myotomy  
Colon resection  
Gastroplasty (gastric banding)

#### *Urology procedures*

Prostatectomy  
Pyeloplasty  
Nephrectomy  
Cystectomy

a benefactor can shorten the time to obtain a return on investment for the institution and helps convince administration. Nonetheless, the recurring costs of robotic accessories, such as disposable robotic attachments, and a yearly maintenance fee of \$100,000 requires either increased unit revenue (fee per procedure), incremental business (increased unit volume for higher fixed costs), or usage fees allocated to users. Training costs (direct and time away from work) for physicians, nurses, and technicians can be significant. The ability to hire new personnel may be limited. In this era of scarce OR nurses and rationing of OR time, the ability to perform more procedures that may not be profitable is sometimes met with skepticism.

Another less quantifiable risk is the alienation of regional physicians and hospitals that could lose patients. If the program is successful, these regional centers may wish to start programs to retain patients or reverse the flow of patients. In terms of health care economics, such scenarios have occurred with imaging modalities, leading to a technological "arms race."

## Market analysis

If the viability of the robotic program depends on surgical volumes, the institution must undertake a market analysis of its service area that encompasses disease prevalence and current surgical volumes. The relationship of surgical volumes to outcomes for surgeries such as radical prostatectomy is well established [7]. Having an outside entity track and publish outcomes for procedures is an increasingly common way to monitor and improve health care outcomes. If the service area is insufficient to supply the needed volume to maintain robotic skills and profitability, marketing must then target an expanded service area. Marketing is defined broadly to include advertising in publications or other media, website, presentations, and notification of referring physicians.

Skepticism and resentment by regional physicians is possible. Being inclusive and offering a training program may be advantageous. In the future, telesurgery, in which the surgeon at a regional hospital is assisted by the robotic center, may be feasible, especially in remote areas [8,9]. The authors' institution serves a predominately rural population with limited access to tertiary health care, and patients often must travel 2 to 6 hours to reach the center. Telerobotic surgery, with training of rural surgeons to assist locally, is an attractive solution.

## Operating room requirements

The OR planning should include time and room availability, room size, room layout, availability of proper receptacles and circuits, imaging (either monitors or three-dimensional room projection), and access to supplies. At the authors' institution, at least 52.2 m<sup>2</sup> is required to accommodate the staff, robot, anesthesia chart, table and three-dimensional projection system (Fig. 1). The authors believe that a dedicated room is optimal to avoid moving the robotic system and risking damage to the mechanical components or wiring. Similar to the experience at Henry Ford Hospital, the authors have found that a dual digital projection system on a silver-coated screen to allow three-dimensional viewing by the first assistant facilitates surgery and allows scrub nurses to follow the surgery and anticipate needs. New operating rooms with three-dimensional projection systems are being designed to aid laparoscopic surgery. Meanwhile, assistants use two-dimensional flat-screen video monitors. There

is a preference for the older cathode ray tube monitors until flat-screen resolution and brightness are commensurate in quality.

Cost-effectiveness of robotic surgery is enhanced with reduced operative time and faster turnover. Thus, any modifications of procedure or technology that lower operative time are essential. Details as small as monitoring the percentage of gas remaining in the carbon dioxide tank allow anticipation of a change, warming of equipment to prevent fogging of the lens, and minimizing retrieval or changing robotic instruments. The authors have used an insufflator system with two tanks of gas that allows switching to a second tank when the first one gets low and then refilling the empty tank to be ready when the second tank empties. The authors try to have enough instruments to perform two cases, which allows back-to-back procedures without having to wait for equipment to be cleaned. The authors also maintain a supply of backup instruments that have been sterilized and are ready to use. Turnover times can be reduced by having a dedicated team that is rewarded for success. In addition, video monitoring of the OR by a surgeon so that inactivity between cases is observed may help minimize lost time.

## Equipment/supplies

There are various questions regarding equipment and supplies. What supplies will be required? Where will they be obtained and how much will they cost? Whose budget will pay for them? How many will be kept in inventory? How many will be sterile and ready at a given time? Where will they be stored and who will be responsible for managing inventory and reordering? Some items may have to be approved by the clinical engineering department, and existing contracts with vendors may preclude purchasing from a competitor.

The items needed to support a robotic program, beyond those already available in the OR, for laparoscopic cases include hardware obtained from the robot vendor: reusable robotic accessories (eg, sterile adapters, scopes, light guide cables, trocars), limited-life reusable robot arms that can be used for 8 to 20 cases depending on the instrument (eg, needle drivers, forceps, scissors, cautery tools), and disposable robotic supplies (eg, drapes, cannula seals).

Other supplies include an insufflator. The authors prefer a heated gas model that is high flow to allow for gas leakage around up to six

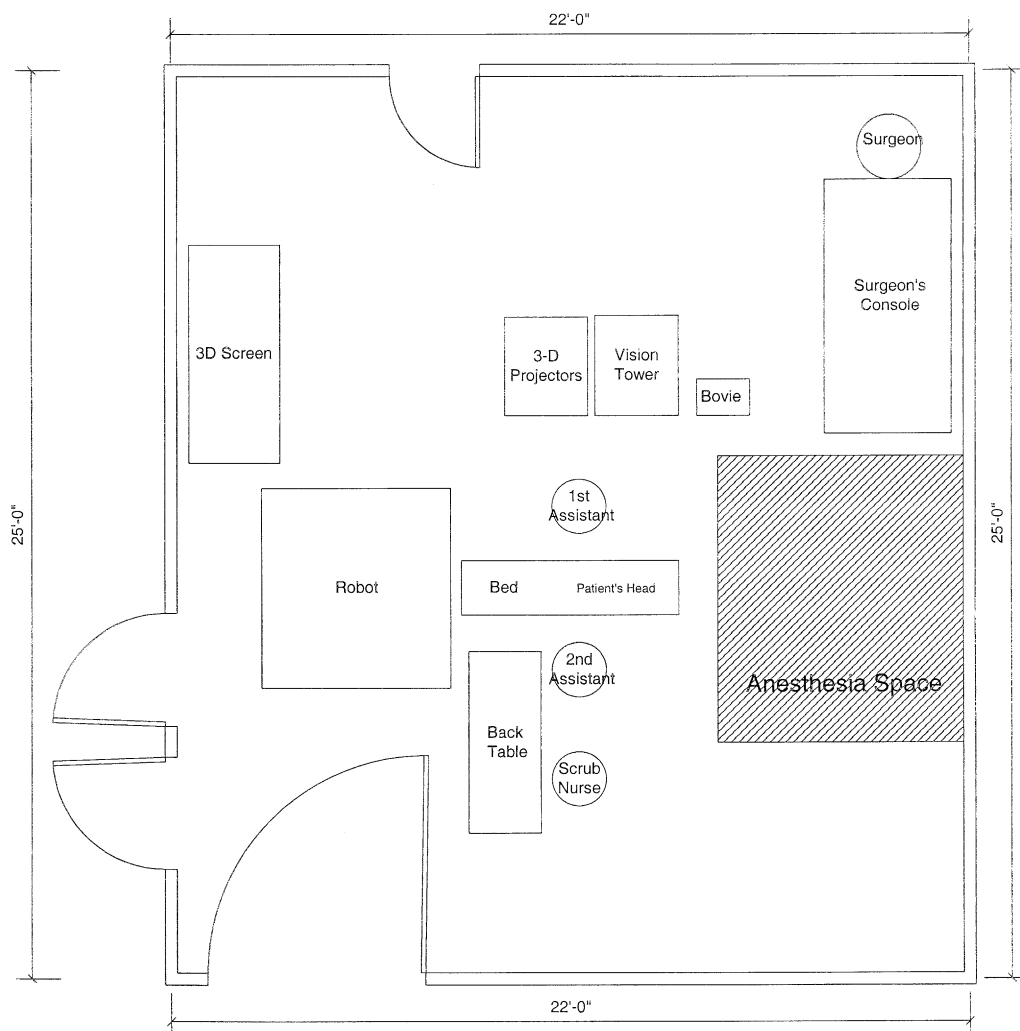


Fig. 1. Robotic prostatectomy room setup.

ports and the urethra. The authors also can switch to a second tank without losing the pneumoperitoneum. Necessary equipment includes a suction irrigator, a scope warmer, a surgeon's chair tall enough to see into the surgeon's console and made of a material suitable for the OR, and video equipment (the authors use a three-dimensional projector and portable silver screen).

### Establishing the robotic team

Robotic surgery is labor-intensive in terms of OR personnel. At least two surgeons, a scrub nurse, and an anesthesiologist are required. Usually a second assistant is necessary but sometimes

can be replaced by a fourth-arm option formerly available on the da Vinci robot. The bedside surgeon must be a fully trained laparoscopic surgeon or surgical technician. Unlike open or other endoscopic surgeries, many robotic surgeries, especially radical prostatectomy, are nearly impossible without an accomplished first assistant [10–12]. The academic medical center needs to decide whether the first assistant is a resident, fellow, faculty member, or surgical technician. This personnel and training decision is complex and has departmental morale and financial implications. Moreover, one scrub nurse may be insufficient to handle imaging, trips to the supply room, or communication with the company if

a malfunction occurs. Thus, a robot company representative is often present. If many new patients are attracted to the institution, additional secretarial and office staff may be necessary. The authors' robotic team, excluding residents, includes 16 people.

A dedicated team of surgeons and nurses is crucial to the successful implementation of robotics. Constantly changing assistants, nurses, and anesthesiologists delays starting times, turnover, and operative time. Optimal rotation time for trainees previously exposed to laparoscopic surgery on robotics should be determined, but the authors' bias is that at least 6 months is necessary. Defining goals, obtaining sufficient training, holding team events such as dinners, and encouraging joint continuing medical education programs will ease the stress when cases go overtime or problems arise. Continual communication among the team with newsletters and follow-up of patients is helpful to maintain esprit de corps. The start-up costs above the capital equipment acquisition and inventory expenses associated with the establishment of a robotics program are summarized in Table 1. This amount of 3-year funding is useful to ensure that a dedicated team is built and maintained, in addition to funding the critical training and marketing expenses essential for program success.

Table 1  
Robotics program 3-year projected additional expenses (exclusive of robot, supplies, and instruments)

Item	Cost
Three-dimensional imaging equipment	\$35,000
Additional robotic operating expenses	
Personnel	
Registered nurses salary and benefits	\$230,000
Program Technician/Project coordinator salary and benefits	\$230,000
Administrative support salary and benefits	\$60,000
Statistician support	\$40,000
Other than personal service expenses	
Training	\$100,000
Marketing	\$200,000
OR team continuing medical education and meetings	\$60,000
Service agreements	\$250,000
Total	\$1,205,000

It may be beneficial to have urology subspecialists in a specific surgery. Specialty teams may minimize problems with positioning, technical nuances, and training time. The authors find that robotic surgery facilitates any laparoscopic surgery that involves suturing because of the proprietary wrist range of motion of the da Vinci system. Ureteropelvic junction reconstruction, urinary diversion/augmentation, and reimplantation are performed [13]. The advantages for pelvic surgeries such as radical prostatectomy and cystectomy are noteworthy [3,12]. The authors have found that the laparoscopic approach is easier than traditional methods in patients who have undergone bilateral inguinal mesh herniorrhaphies because less dissection is necessary and exposure is improved without retraction. Blood loss is dramatically less because pneumoperitoneum reduces venous oozing. Less venous bleeding requires less cautery and subsequent tissue injury. Postoperative pain is less than open surgery, not only because of less retraction and shorter incisions, but because inflammatory cytokines (interleukins) and nociceptive compounds (bradykinins) are reduced with carbon dioxide pneumoperitoneum [14,15]. Probably the greatest advantage is the dramatic improvement in visualization in three dimensions, not achieved with traditional laparoscopic cameras. This visualization may allow better preservation of neurovascular and muscular structures. The authors believe that what is lost by a lack of tactile feedback is more than compensated for by improved visualization.

The adoption of robotic surgery by other surgeons helps ensure success of the program, although it limits urologic use. Originally developed for cardiovascular surgery, robotics has been used by general surgeons, microsurgeons, head and neck surgeons, and gynecologists.

## Training

One of the highest barriers to laparoscopic surgery has been the training necessary to acquire skills and perform increasingly complex surgery. Robotics reduces the learning curve for laparoscopic surgery [16]. Collective experience shows that the surgeon at the console need not have trained as a laparoscopic surgeon if there is a capable assistant at the bedside [5]. In fact, unlike skilled laparoscopic surgeons, the laparoscopically naïve surgeon at the console need not unlearn certain skills, such as suture tying in two dimensions. Nonetheless, extensive training is

needed beyond a short (several-day) course and should not be underestimated.

Short courses including an animal laboratory and use of models may familiarize the console and bedside surgeons and team with the equipment, general principles, and techniques, but repetition of actual surgery is undeniably the best approach. On-site mentoring often is not feasible, and this may necessitate a sabbatical at a high-volume center. Proctoring for the first several surgeries is highly advisable. The indirect costs of training must be factored into the business plan and the career aspirations of the surgeon need to be taken into account.

Surgical training consists of two equal components: use of the robot and the surgical procedure. Training on the robot using models is required to learn the response of the robotic arms and suturing. Laparoscopic training includes specialized port placement and other techniques used by the bedside team. Proper patient positioning and port placement are crucial. Training in surgical technique begins with porcine surgery, review of videos, watching numerous procedures, and then completing various steps of the procedure before attempting an entire case. The transition from animal surgery to humans is problematic because of subtle differences in anatomy, including tissue planes and amount of adipose tissue, not to mention the controversy surrounding animal experimentation. Just as important as training on the console is the training of the laparoscopic cosurgeon. This individual needs to know and anticipate each step to facilitate surgery and reduce operative time. Slow adaptation to robotics and lengthy operative times may result from a lack of skilled cosurgeons.

There is growing recognition that surgeons in training will be required to use simulated surgery before operating on patients. Clinical competencies for residency training require objective and quantifiable measures of procedural skills. This will force the adoption of surgical simulators similar to those used to train pilots and other professionals. Endoscopic simulators such as the URO Mentor (Simbionix Corp., Cleveland, Ohio) have advanced sufficiently to become important training tools in residency training programs [17]. Robotic surgery lends itself to simulated learning better than open surgery does. The development of a virtual reality training system for robotics would lessen the learning curve and help the rapid adoption of this technology by allowing quantification of skills [18,19].

The full benefits of establishing a robotics program have yet to be realized. For example, the cost and time involved in training a surgeon are enormous. Often surgeons reach peak performance in their 50s. In rare instances, a surgeon may sustain an injury, such as a cervical disk herniation, that limits or ends a surgeon's operative career. Such a surgeon potentially could perform surgery using robotic technology.

### **Establishing a timeline**

The timeline to achieve various landmarks will vary among institutions. It is reasonable to plan for 6 to 12 months to enable financing, 1 to 3 months for training, 1 to 3 months for OR renovation and 2 to 4 weeks for installation. Expect 6 to 12 months to ramp up the program, which may plateau 12 to 18 months later. Some programs may then contemplate expansion with another robot if enough surgery is performed, or with development of a training program. The development of a robotics program is measured in years, not months.

### **Research issues**

Some have argued that robotics is a technology looking for a use. Using a robot for some procedures is similar to driving a Lamborghini in second gear. Its full potential is unknown. Academic medical centers should engage actively in research in cooperation with industry and position themselves to take robotics to the next level. Beyond outcome research, the authors are pursuing advanced bioimaging, telerobotic mentoring and surgery, and expansion of surgical indications. Preliminary reports on using the da Vinci robot to perform tedious cavernous nerve grafting after prostatectomy recently appeared [20,21]. It may become feasible to perform bladder transplantation with nerve grafting. Preprogramming specific operative steps based on fixation of tissues and intraoperative imaging with the establishment of three-dimensional coordinates may be an attainable goal. Novel uses can be expected to appear over time, given sufficient interest and research funding.

### **Monitoring outcomes and success**

The implementation of a robotics program should include defining specific measurable

objectives for caseloads to be attained over the baseline volumes. The metrics to evaluate the success of the program would be surgical volume compared with baseline. Outcome measures specific to the procedure such as continence, potency, blood loss, analgesic requirements, tumor margins, and prostate-specific antigen levels following prostatectomy at various intervals must be assessed. Additional quality assessment is based on (1) customer satisfaction, (2) performance over time against University Health Care Consortium and national benchmarks, (3) performance over time on internally designed quality performance measures, and (4) overall quality-of-life instruments.

Customer satisfaction includes referring physician satisfaction and patient satisfaction. Both should be surveyed qualitatively and robotic surgery patients should be surveyed specifically for their satisfaction with their surgery. The authors' initial patient satisfaction assessment has been qualitative, and shows most patients are satisfied. Feedback from these patients is being used to develop a patient satisfaction survey. The authors ask patients, following their surgery, if they were satisfied with the accuracy and completeness of information on what to expect, convenience of scheduling, and minimizing the number of trips to the Medical Center throughout the process. Patients are asked them how user-friendly the system is for calling and asking clinical, logistical, or financial questions.

Performance over time against benchmarked data for morbidity, including complications, average length of stay, charges, cost per case, and tumor margins should be evaluated. The authors have captured some of these items. For example, for the authors' initial 12 robotic radical prostatectomies, hospitalization averaged 1.5 days, average blood loss was 215 mL, and pain levels were between 0 and 2 (on a scale from 1–10 with 10 being the most pain) on the day following surgery and 0 on the date of discharge.

Performance over time on internally designed quality performance measures will test whether the combination of robotic surgery with emergent biomedical imaging modalities will compensate for the lack of haptic feedback. In future studies, outcomes will be measured and analyzed to assess this hypothesis.

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## Role of robotics in laparoscopic urologic surgery

Louis Eichel, MD, Thomas E. Ahlering, MD,  
Ralph V. Clayman, MD\*

*Department of Urology, University of California Irvine, 101 The City Drive South,  
Building 55, Room 304, Orange, CA 92868, USA*

The field of robot-assisted surgery is in its infancy and indications for its use in urologic surgery are expanding. There is a rich tradition in urology of using advanced technology to make procedures easier, more exact, and more tolerable. Just as Bozzini used an aluminum tube fitted with mirrors and illuminated by a wax candle to visualize the urethra in 1806, urologists today constantly seek new and better ways to practice their craft. The integration of modern computers, digital-imaging equipment, and robotic technology offers urologists new opportunities to improve their surgical technique and challenge their abilities.

Great strides have been made in the last decade with the widespread development of laparoscopic skills among urologists. The number and complexity of surgical cases being performed is growing. Still, however, technical limitations cause a steep learning curve for many laparoscopic procedures.

Using robotic surgical systems to perform minimally invasive procedures offers many potential advantages. Unlike the two-dimensional visual images provided by most modern laparoscopic systems, some telerobotic systems with motorized camera arms provide steady three-dimensional images with the type of depth perception surgeons are accustomed to with open surgery. Other systems provide a steady, tireless arm to hold and guide a standard lens/camera system, or provide image-guided needle placement. Compared with standard laparoscopic instruments that grant the surgeon four degrees of freedom, modern robotic instruments commonly provide six or seven degrees of freedom, more closely mimicking

the actual movements of a human hand and wrist. The combination of improved visualization and enhanced dexterity shortens the learning curve for more complex procedures. Other systems of recent and historic significance use stereotactic guidance systems to perform percutaneous needle access to the renal collecting system or transurethral resection of the prostate.

It is unclear if the greater precision and improved visualization provided by these systems will translate into superior surgical results. Because the field is in its infancy, long-term follow-up for robot-assisted procedures is not available and variations in surgical skills and operative technique remain confounding factors. Clearly, however, as these new technologies develop, the shortened learning curve that they provide will allow more urologists to provide their patients technically proficient and less-invasive operations. This article summarizes the historic development, current status, and future directions of robotic applications in urologic surgery.

### The history of surgical robotics

Kwong and colleagues [1], who used a modified light-duty industrial robotic arm to guide a laser for stereotactic brain surgery, described the first robot-assisted surgery in 1985. Davies and colleagues [2], who used a modified industrial robotic arm to perform transurethral resection of the prostate in humans, described the first robot-assisted procedure on soft tissue 4 years later. A more recent urologic application of robotics (in the experimental phase) is a robotic system used to gain fluoroscopically guided percutaneous access to the renal collecting system [3,4]. The first

\* Corresponding author.

E-mail address: [rclayman@uci.edu](mailto:rclayman@uci.edu) (R.V. Clayman).

commercially available robotic system, RoboDoc, was described in 1992. This was a robotic arm designed to core out femoral shafts precisely for hip prostheses. In a randomized trial of RoboDoc coring versus hand coring in 136 patients, the RoboDoc increased operative time and blood loss, but resulted in a better fit for the prosthesis. There were three femoral fractures in the hand-cored group versus none in the RoboDoc group [5].

The first commercial robotic system used specifically for laparoscopic applications was the Automated Endoscopic System for Optimal Positioning (AESOP). The AESOP is a table-mounted robotic arm that precisely manipulates a standard laparoscope or instrument. This system was designed initially using seed funding from the United States military, but went into commercial production by Computer Motion (Sunnyvale, California). In 1993 AESOP became the first surgical robotic system approved by the US Food and Drug Administration (FDA) and remains one of the most widely used systems because of its versatility.

The AESOP was not the only project of this nature initially supported by the United States military and ultimately licensed by private industry. The predecessor to the three-armed da Vinci system (Intuitive Surgical, Sunnyvale, California) first was conceptualized by researchers at the US National Aeronautics and Space Administration, and later at the Pentagon [6]. This system originally was intended to allow surgeons in a mobile advanced surgical hospital unit to operate on wounded soldiers who were located in the back of a Bradley fighting vehicle equipped with a robotic surgical system.

This concept of remote telemanipulation has remained a central theme in modern surgical robotic systems. The da Vinci system was used clinically first for laparoscopic cholecystectomy in 1997 and gained FDA approval the same year. This system provided an array of instruments with six degrees of freedom (Endowrist, Computer Motion), greatly enhancing the laparoscopic capabilities of the surgeon. Shortly after, the ZEUS system (Computer Motion) came onto the market in 1998. This system combined an AESOP system with two additional table-mounted robotic arms. At the time, the ZEUS system had instruments with four degrees of freedom (like standard laparoscopic instruments), but in 2002 MicroWrist instruments gained FDA approval. In 2003, Intuitive Surgical and Computer Motion, the two leaders in robotic surgical technology, merged. As a result, the ZEUS system is supported for parts

and service, but no new sales are being made. Thus, the only commercially available multifunctional telerobotic surgical system is the da Vinci system.

## Modern surgical robotic systems

### *Classifications of modern surgical robots*

Modern robotic surgical systems fall into three categories: active, semiactive, and master-slave systems [7]. Active systems have artificial intelligence that allows them to perform a procedure autonomously under the supervision of the surgeon. RoboDoc [5], the prostatectomy Probot [2,8], and the percutaneous access to the kidney (PAKY) system [3,4,9] are modern examples of this type of system. Semiactive systems have an automatic and a surgeon-driven component. For example, the surgeon uses a mechanical guide positioned by the robot to perform a biopsy or place a needle-ablative probe. In contrast, teleoperated master-slave systems allow the surgeon to operate the robot directly from a remote command center. There is no autonomous component of robotic action. The surgeon's movements or commands are translated into robotic motions. Most systems commonly used in urologic surgery fall into this category (eg, AESOP, ZEUS, da Vinci). With these systems, telesurgery is possible because the surgeon can be in the same room or in a different country, depending on the situation [10–15]. All that is required is a signal of sufficient speed to avoid prohibitive time delays (greater than 300 milliseconds) between the surgeon's commands and the robotic movements [16].

### *Automated endoscopic system for optimal positioning*

AESOP is a table-mounted, voice-activated robotic arm with seven degrees of freedom that can be used to manipulate a standard laparoscope, thereby eliminating the camera-holding assistant (Fig. 1). It is controlled by the primary surgeon and provides a smooth, precise, and stable view of the surgical field. From a urologic standpoint, this device has been studied most closely at Johns Hopkins University. In that institution's earliest clinical study, robotic versus hand manipulation was compared in 11 pelvic procedures requiring symmetric bilateral camera manipulations. The authors found that AESOP assistance decreased unwanted camera movements, providing a better camera image without increasing operative time [17].



Fig. 1. The AESOP robotic system. (Courtesy of Intuitive Surgical, Inc., Sunnyvale, CA; with permission.)

The value of AESOP for providing a steady image during pelvic laparoscopic procedures has been validated by larger series of laparoscopic radical prostatectomy in which having the robotic arm provide a steady, durable view of the pelvis frees the hands of the assistant [18]. In a subsequent series of 17 patients by the Hopkins group, the AESOP was used for nephrectomy, ureterolysis, and pyeloplasty with excellent results [19]. This study also found it to be cost-effective. At the 1995 purchase price of \$25,000, if the robot was depreciated over 5 years and worked a 5-day week at 5 hr/d, then the hourly cost, including

maintenance and storage, was \$3.85. Because the current cost of AESOP is \$130,000, however, its cost-effectiveness needs to be reassessed. Overall, the AESOP has been a safe and effective adjunct to standard laparoscopy. It is particularly well suited for procedures in which the increments of camera movements are short (eg, pelvic procedures). For procedures that require many sweeping camera movements, such as nephrectomy, the slowness of the camera movement becomes problematic.

### ZEUS

The ZEUS system is a master-slave telerobotic system that consists of three table-mounted robotic arms (Fig. 2). One arm is an AESOP unit that holds and manipulates the laparoscope. The other two arms manipulate robotically driven laparoscopic instruments. The ZEUS system hosts various standard (nonarticulating with four degrees of freedom) and unidirectional articulating instruments that have six degrees of freedom. The instruments are reusable and fit through standard trocars. The laparoscope is driven by voice command and the robotic instruments are driven from an ergonomically designed surgeon's console. The surgeon sits comfortably at a workstation and the hand controls are positioned in the correct hand-eye axis for optimal dexterity [6]. Two- and three-dimensional viewing options are available. The ZEUS system is no longer commercially available.



Fig. 2. The Zeus robotic system. (Courtesy of Intuitive Surgical, Inc., Sunnyvale, CA; with permission.)

Intuitive Surgical provides support for the system, however, and according to the company, a phase-out and replacement program is underway.

### *da Vinci*

The da Vinci robotic surgical system is a master-slave system consisting of a freestanding robotic tower and a surgeon console (Fig. 3). The robotic tower has a camera arm and two or three instrument arms. The surgeon's console provides a 6× to 10× magnified three-dimensional image of the surgical field and an ergonomically designed interface that allows the Endowrist articulated instruments with seven degrees of freedom: in, out, left, right, up, down, rotational axis, pitch, yaw, and grip. The bidirectional articulation and grip mimic the actual hand and wrist movements of the surgeon. The surgeon's hand-eye axis is positioned to create the illusion of operating directly on the patient. Unlike the ZEUS system, the da Vinci system's instruments have a limited number of uses and therefore add to the cost of the procedure. The current cost for a da Vinci system is \$1.09 million for a three-arm system and \$1.285 million for a four-arm system. Service is free for the first year and costs \$109,000 to \$125,000 per year thereafter. Instruments cost \$180 per case, multiplied by the number of instruments used per case. Neither the ZEUS nor the da Vinci system has force (haptic) feedback. The da Vinci is the only commercially available telesurgical system.

## **Robotic-assisted renal procedures**

### *Percutaneous renal access*

Through the pioneering efforts of the Urobotics Laboratory at Johns Hopkins University, a fluoroscopically guided robotic system for percutaneous needle placement with a remote-center-of-motion device (PAKY-RCM) is under experimental use [3,9,20]. PAKY-RCM consists of a radiolucent, automated needle advancement system that is mounted on a low-profile, remote center-of-motion robotic arm that fits within the constraints of most modern C-Arm fluoroscopes and CT scanners. The system has been used in the laboratory setting as well as clinically with excellent results. In a head-to-head trial of 23 patients accessed using the PAKY-RCM versus a contemporaneous group of patients accessed by hand, there were no differences in access rate, number of needle sticks, or blood loss [4]. PAKY-RCM is being developed further to be compatible with standard fluoroscopic imaging equipment [20].

### *Robotic laparoscopic nephrectomy*

Guillonneau and colleagues [21] performed the first robot-assisted laparoscopic nephrectomy in 2001. There has not been a large published series regarding robotic radical nephrectomy since then. Horgan and colleagues [22], however, reported their early experience with donor nephrectomy in 12 patients. All procedures were completed



Fig. 3. The da Vinci robotic system. (Courtesy of Intuitive Surgical, Inc., Sunnyvale, CA; with permission.)

successfully. The operative results were similar to standard laparoscopic donor nephrectomy. The authors concluded, however, that the robotic system, with its many advantages over standard laparoscopy, made dissection easier and less stressful.

Nephrectomy is mainly an extirpative procedure, which may explain why surgeons have been slow to adopt the use of robotic technology to perform nephrectomy. The marked advantages for suturing and reconstruction are not needed. Marell and colleagues [23] recently confirmed this concept in a study in which 18 robotic laparoscopic nephrectomies were compared with 23 hand-assisted laparoscopic nephrectomies. The two procedures were equivalent except for operative time, where robotic nephrectomy took considerably longer to perform (361 versus 181 minutes). The authors did not report time until return to full activity, however. Although no clear advantage to robotic nephrectomy is evident, the use of a robotic system may make it possible for beginner laparoscopists to perform nephrectomy, thereby making the procedure available to more patients, including potential donors.

#### *Laparoscopic partial nephrectomy*

In contrast to total nephrectomy, laparoscopic partial nephrectomy requires complex dissection and intracorporeal suturing, for which a robotic interface may offer advantages. Two small series of adult robotic partial nephrectomies have been reported. Taneja and colleagues [24] reported 10 cases with a mean tumor size of 2 cm. All tumors were exophytic and the renal artery was occluded using a bulldog clamp in all cases. The mass was exposed using standard laparoscopic techniques. The robotic system was used to excise the mass using cold scissors and electrocautery followed by suturing of arterial branches. Renorrhaphy was performed using thrombin-soaked Gelfoam (Pfizer, New York, New York) and sutures. There was one conversion to a hand-assisted approach and one open conversion for intraoperative bleeding. Margin status and warm ischemia times were not reported.

In a separate series, Peschel and colleagues [25] reported their experience with 13 partial nephrectomies (12 purely robotic) with a mean lesion size of 3.5 cm. In eight cases an intra-arterial catheter was used for renal cooling. The tumors were excised using cold scissors and robotic suturing was used to repair the collecting system and for

renorrhaphy. The mean warm ischemia time was 22 minutes and cold ischemia time ranged from 18 to 43 minutes. Mean estimated blood loss was 170 mL. Mean operating time was 215 minutes. Ten cases had malignancies. There was one positive margin in a patient with a 6-cm tumor. This was treated with complete nephrectomy.

#### *Robot-assisted laparoscopic adrenalectomy*

Desai and colleagues [26] first reported robot-assisted laparoscopic adrenalectomy in 2002. They successfully performed two transperitoneal robot-assisted adrenalectomies, one left and one right, each in less than 3 hours with minimal blood loss and satisfactory recovery using the da Vinci robotic system. For either side, an extra assistant's port was needed in addition to the three robotic ports, and on the right side a 5-mm xiphoid liver retractor port also was needed. Bentas and colleagues [27] reported equally successful results in a series of four patients using the da Vinci system. The authors stated that although they were not "expert" laparoscopic surgeons, their experience with robotic prostatectomies helped them to succeed in adrenalectomy. An additional development in this relatively new procedure is a recent report of five successfully telementored robotic adrenalectomies between Modena and Turin, Italy.

#### *Laparoscopic pyeloplasty*

Schuessler and colleagues [28] first reported laparoscopic pyeloplasty in 1993. Since then, the procedure has become accepted increasingly, with modern series reporting results similar to open pyeloplasty [29]. The technique of dismembered pyeloplasty has not, however, become accepted as rapidly as laparoscopic nephrectomy. One main reason is that the precise intracorporeal suturing required is time-consuming and requires advanced laparoscopic skills.

The recent advances in robotic surgical systems such as the da Vinci system have simplified intracorporeal suturing greatly. Sung and colleagues [30,31] first explored the concept of robot-assisted pyeloplasty (RAP). They performed the procedure in pigs and reported excellent visualization, easy suture placement, and no significant complications. Following this, the first clinical experience with robot-assisted pyeloplasties provided satisfactory results in a limited number of patients [32,33]. Additionally, one recent study comparing contemporary groups of standard laparoscopic versus da Vinci-assisted pyeloplasty showed costs

of \$10,798 versus \$11,897 per case, respectively [34]. The \$1,000 difference was largely a result of the cost of disposables and the overall cost/service contract associated with the da Vinci system.

At the University of California (Irvine) the authors have performed 13 pyeloplasties robotically. A retrospective review of these cases was compared with the same surgeons' last 10 standard laparoscopic pyeloplasties. Compared with standard laparoscopy, there was no significant difference in mean total operating time despite the time needed to dock the robotic system. Hospital stay was significantly shorter in the robotic group, but the robotic group had a significant delayed complication: a jejunal injury that presented on postoperative day 13 and was repaired successfully at open exploration. There were no complications in the standard group. Follow-up results were not available for one of the standard patients. At a mean follow-up time of 11 months, all robotically treated patients had no evidence of obstruction on renal scan (mean time until half of tracer remains in pelvis ( $t_{1/2}$ ) = 12.6 minutes) and 12 of

the 13 patients were pain-free (mean score on analog pain scale 0.5 of 10). In the standard group, all patients had no evidence of obstruction on renal scan or Whitaker test at a mean follow up of 2 months, but subjective follow-up was only available for three of eight patients. At a mean follow-up of 3 years, one had significant pain and two were pain-free. Table 1 summarizes results of recently reported series of robotic pyeloplasties.

In summary, laparoscopic dismembered pyeloplasty is a technically challenging procedure that requires expert suturing. The authors' data as well as other recent studies and a case report [32,33,35] show excellent initial results using a robot-assisted interface.

#### *Robot-assisted laparoscopic radical prostatectomy*

Standard laparoscopic radical prostatectomy (LRP) is a technically demanding procedure that requires expert laparoscopic dissection and suturing skills. It has been estimated that a seasoned laparoscopic surgeon takes 40 to 80 cases to

Table 1  
Results of robotic laparoscopic dismembered pyeloplasty series

Series	Gettman and colleagues [32]	Kozlowski and colleagues [33]	Munver and colleagues [58]	Patel [59]	Hubert and colleagues [60,61]	University of California, Irvine series
No. technique	9	8	15	10	22	13
Operating time (hr)	2.3	4.5	3.1	3.5	2.5	5.9
Estimated blood loss (mL)	<50	50	37	58	—	71
Hospital stay (d)	4.7	2	3.1	0.75	7.2	2
Analgesia postoperative (mg magnesium sulfate)	—	—	—	—	—	38
Return to work/normal activity (d)	—	—	—	11/18	—	—/32
Complications (%)	11	0	0	0	13.6 UTI	7.6
Conversions	—	0	0	0	1	0
Mean follow-up/results	4 mo <sup>a</sup>	3 mo/all with no obstruction on IVP	9.7 mo/all pain-free with patent UPJ	5 mo/all with improved renal scan	3 mo <sup>b</sup>	11 mo/mean $T_{1/2}$ = 12.5 min; 12 patients pain-free

All procedures successful based on symptom resolution and radiographic imaging.

Abbreviations: IVP, intravenous pyelogram; UPJ, uteropelvic junction; UTI, urinary tract infection.

<sup>a</sup> Follow-up available for five patients. These patients were radiographically and subjectively normal.

<sup>b</sup> All patients had clinical improvement after removal of the double-J stent. Of the 19 available postoperative IVU, 18 had good excretion at 10 minutes and one was slightly improved.

overcome the steep learning curve associated with this procedure. In contrast, the enhanced imaging capabilities and easily manipulated articulating instruments afforded by the da Vinci system have shortened the learning curve markedly in several studies, even for laparoscopically naive surgeons, to approximately 20 cases [36–38]. Table 2 summarizes the results of several initial experiences with robot-assisted laparoscopic radical prostatectomy (RLRP), which affords patients similar benefits to those of LRP.

Additionally, early results from several series in which surgeons transitioned from open radical prostatectomy (RP) to RLRP have shown equal or better results compared with open surgery [39–41]. In two recent papers, Menon and colleagues [40] and Ahlering and colleagues [41] compared their institutional and personal results with open radical prostatectomies to their experience with RLRP. The RLRP operative times were similar to the RP operative times, but there were significant reductions in estimated blood loss, transfusion rate, hospitalization time, catheterization duration, and perioperative complications with RLRP. Both groups reported similar oncologic outcomes (positive margins 15%–18%) and continence rates (75%–80% no pads at 3 months). Data on potency are relatively immature, but both groups have indicated results similar to their experience with open surgery (55%–65% for those <60 years of age and 40%–50% for those >60 years of age at 1 year).

#### Robotic radical cystectomy

Menon and colleagues [42] first described their experience with robotic radical cystectomy (RRC) in 17 patients (14 male and three female) in 2003. The robotic system was used to perform a cystoprostatectomy and bilateral pelvic-lymph node

dissection. Removal of the specimen and bowel reconstruction was performed extracorporeally through a 6-cm suprapubic incision. Finally, the neobladder-urethral anastomosis was completed using the robotic system. The mean operative times for robotic radical cystectomy, ileal conduit, and orthotopic neobladder were 140, 120, and 168 minutes, respectively. The mean blood loss was less than 150 mL. The number of lymph nodes removed was 4 to 27, with one patient having N1 disease. The margins of resection were free of tumor in all patients. Success with RRC has been repeated by others [43].

Subsequently, Beecken and colleagues [44] described the technique for robotic intracorporeal neobladder reconstruction in a case report. The procedure took 8.5 hours and the specimen was removed by an entrapment sack through an extended incision at the conclusion of the case. Thus, with increasing experience using bowel for urinary reconstructions, urologists likely will begin to use robotics more extensively for various types of urinary reconstruction and diversion [45].

#### Robotic sacrocolpopexy

Similar to radical prostatectomy, laparoscopic sacrocolpopexy is a pelvic operation that is well suited to a robotic interface. The main advantage over standard laparoscopy is facilitation of the intracorporeal suturing and reconstruction, although the binocular vision and articulating instruments aid in dissection as well. The largest series of cases reported in the literature includes five patients in whom the initial dissection was performed using standard laparoscopy and the da Vinci system was used to perform the reconstructive portion of the procedure [46]. All patients had grade-3 or -4 vaginal prolapse and three had concomitant stress urinary incontinence. The

Table 2  
Perioperative parameters of reported robot-assisted laparoscopic radical prostatectomy series

Authors	n	Mean PSA	Operating time (hr)	EBL (cc)	No. hospital days	Total complication rate	Positive margin rate (overall)	pT2 cancer	pT3 cancer
Rassweiler [62] <sup>a</sup>	33	8.8	6.25	—	—	—	18%	—	—
Menon [63]	100	7.2	3.25	149	95% < 24 hr	8%	15%	10.5%	40%
Bentas [37]	40	11.3	9.9	570	17	25%	30%	8%	67%
Wolfram [64]	81	8.9	4.1	300	—	—	22%	12.7%	42%
Ahlering	60	8.1	3.85	103	1.1	6.7%	16.7%	4.5%	50%

Abbreviations: EBL, estimated blood loss; PSA, prostate-specific antigen.

<sup>a</sup> European meta-analysis of three centers.

mean operative time was 3 hours and 42 minutes, and all patients were discharged on postoperative day 1. The three patients who had stress incontinence also had placement of a pubovaginal sling. At 1 month follow-up there were no recurrent instances of prolapse.

At the University of California (Irvine), two completely robotic sacrocolpopexies have been completed. Both patients had transvaginal cystocele repair and placement of a tension-free urethral sling. The robotic case times were 55 minutes and 105 minutes. The patients were discharged on postoperative day 2 and 1, respectively. The first patient is without vaginal wall laxity or incontinence 7 months postoperatively. The second patient had a mild degree of stress incontinence but no vaginal wall laxity 2 months postoperatively [47].

#### *Vesicovaginal fistula repair*

Several techniques exist for repairing a vesicovaginal fistula. Vaginal repairs offer the least morbidity to the patient but can be technically challenging for posterior fistulae. Well-selected patients treated in experienced centers, however, have a success rate of 88% to 100% [48]. Abdominal and transvesical approaches offer excellent results (85%–100%) for fistulae in difficult locations, but the increased morbidity is significant in comparison. There have been several reports of laparoscopic repairs [49–51]. This approach combines the advantage of decreased morbidity with potentially the same success rate as abdominal repair, even for difficult posterior locations. Unfortunately, the technique has not gained popularity, likely because of the need for complex laparoscopic suturing.

At the University of California (Irvine), the da Vinci system was used for the first time to repair a posterior fistula in a 44-year-old woman who originally had had a vaginal hysterectomy for uterine fibroids. In this procedure, the da Vinci system was docked after standard laparoscopic dissection of the fistula through a generous cystotomy. With the da Vinci system, the vaginal layer was closed as a single layer using 3-0 absorbable braided suture on an SH needle (Fig. 4). The bladder was closed in two layers: a mucosal layer followed by a seromuscular layer with 3-0 absorbable braided suture. Fibrin glue was injected between the bladder and vagina to separate the suture lines.

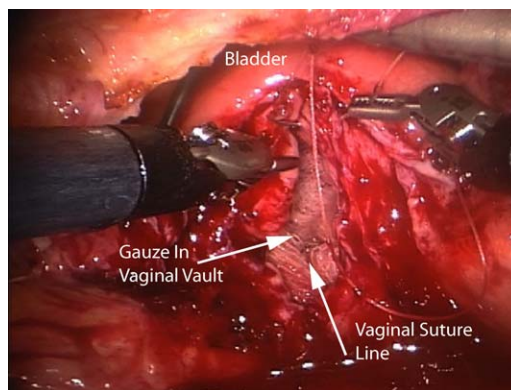


Fig. 4. Robotic suturing of the vaginal defect following fistula excision. A 10 cm × 10 cm sponge rests within the vaginal vault to prevent loss of pneumoperitoneum.

The total operative time was 280 minutes with an estimated blood loss of 50 mL. The patient went home on the second postoperative day. The Foley catheter was removed at 2 weeks. At 6 weeks follow-up, she is asymptomatic with normal voiding.

#### *Robotic vasovasostomy*

The 12× magnification, stable platform, and motion scaling offered by the robot make it an ideal tool for microsurgical applications in urology. In a recent randomized prospective study of robotic versus standard microsurgical vasovasostomy and vasoepididymostomy in a rat model, Schiff and colleagues [52] reported that the improved stability and motion reduction during microsurgical suturing provided by the robotic system reduced anastomotic time significantly in the robotic vasovasostomy group (102.5 versus 68.5 minutes, respectively). Trends toward improved patency rates (100% versus 90%) and reduced incidence of sperm granulomas (27% versus 70%) also were evident but did not reach statistical significance.

#### *Pediatric urologic applications of robotic surgery*

More pediatric urologists are using a laparoscopic approach for diagnostic, organ-ablative, and reconstructive purposes. Small series and case reports of robot-assisted approaches to these procedures are emerging. Cisek and Jones [53] compared an experienced surgeon to an inexperienced surgeon performing robotic suturing for Lich-Gregoir-based ureteroneocystotomies. There

was a significant time difference between the experienced surgeon and inexperienced surgeons for standard laparoscopic suturing (3.4 versus 8.4 minutes, respectively), but robot-assisted suturing times were similar (3 versus 3.3 minutes, respectively). Thus, the feasibility of this technique and the advantages of a robotic interface for overcoming the learning curve inherent in standard laparoscopy were demonstrated.

There are few reported cases of transperitoneal robotic pyeloplasty in children [54], including one series of 31 patients with a mean age of 9.6 years treated with a retroperitoneal approach. Olsen and Jørgensen [55] reported 31 successful retroperitoneal pyeloplasties using the da Vinci system with the patient in the lateral semiprone position.

Case reports of robotic appendicovesicostomy [45] and heminephroureterectomy [56] exist in the recent literature, but experience with these procedures is anecdotal. Animal studies for pediatric robotic applications are underway. Olsen and colleagues [57] report a porcine experiment using the da Vinci system to accomplish a Choen uretero-neocystostomy using a pneumovesical approach. Three months postoperatively all eight pigs treated had no evidence of reflux.

### Future applications of robotic technology

Robotic surgical technology is in its infancy. Never has there been such cooperation and collaboration among physicians, engineers, and computer scientists. Soon, emphasis will be placed on miniaturization and simplification of existing systems. For example, Intuitive Surgical is developing 5-mm instruments that will feature enhanced motion freedom, modular tips, and smoother rolling action; these instruments will be ideal for adult and pediatric surgery. In addition, a two-dimensional, wide-angle view will be integrated into the lens system. Future robotic systems also may incorporate a three-dimensional vision system for the assistant so that the surgeon and assistant have the same view. Integrated telestration systems will allow proctors to teach more easily and will aid in resident education and training.

Major technologic advances will come as integrated operating room systems are developed. Specialized suites would be equipped with ceiling- and table-mounted robotic units that perform individual functions. Real-time imaging equipment as well as image-guidance systems will be integrated to provide real-time imaging and

robotic targeting of the patient preoperatively and intraoperatively. Computer-based planning systems will aid in port placement and plan of dissection. Intraoperatively, real-time imaging will be displayed on a multiple input–integrated screen system along with other parameters of interest such as vital signs and elapsed time. Telerobotic systems also offer the opportunity for telepresence collaboration among multiple surgeons from remote locations. Thus, as the interconnectivity of the world grows, so will one's ability to collaborate using these systems.

Finally, the most recent developments in robotic technology have not begun to be applied to medicine. One major focus is on miniaturization of robots to extremes that would allow them to roam within the human body. Recently, a miniature robot was designed at Sandia National Laboratories (Albuquerque, New Mexico) that is 1.63 cm<sup>3</sup> in size (Fig. 5). Plans to mount cameras, temperature sensors, microphones, microtools, or other miniaturized equipment are in development.

The only factors limiting the size of autonomous robots are the battery and battery life, but this issue largely has been circumvented already. The Norika 3 endoscopic capsule developed by RF SystemLab (Nagano City, Japan) is a 9 mm × 23 mm ingestible capsule, autonomously powered, remote-controlled microrobotic system that has a video imaging system (Fig. 6). The capsule is designed to be manipulated around the gastrointestinal tract for diagnostic imaging. The capsule endoscope NORIKA system consists of a microcapsule charge-coupled-device camera, an external controller to control and operate the capsule



Fig. 5. Minirobot designed at Sandia National Laboratories, Albuquerque, New Mexico. (Courtesy of Sandia National Laboratories, Albuquerque, New Mexico; with permission.)

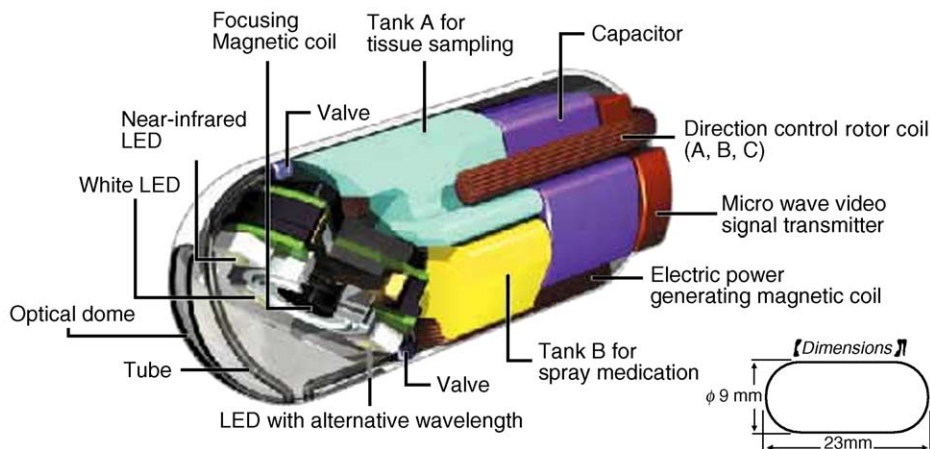


Fig. 6. The NORIKA 3 microrobotic endoscopic camera. (Courtesy of RF SystemLab, Nagano, Japan; with permission.)

wirelessly, and a coil-embedded vest for power transmission and direction control. The case is made of resin. Three rotor coils for posture control surround the capsule. Magnetic coils for focus adjustment and four light-emitting diodes are placed around the camera lens. For power, an onboard capacitor stores electric power and a microwave video signal transmitter sends information outside the patient. The entire unit is controlled by a joystick-operated command station where the operator views the video image. Plans are in development for an onboard pneumatic medication administration system as well as other microtools, such as pH or heat sensors and

lasers. The urologic applications of such a device are numerous.

Taking the concept of nanorobotics one step further, a microrobotic device, such as the NORIKA 3, recognizing a pathologic situation, could deploy pneumatically an entire army of protein-based nanorobots that are powered autonomously by ATP motors or other biomolecular actuators. These nanorobots equipped with DNA joints and carbon-nanotube rigid links could have multiple degrees of freedom and perform specific functions such as repairing (or destroying) individual cells (Fig. 7). The potential for self-replication and self-assembly exists.

### Summary

Robotic surgery is in its infancy. Small series of cases are emerging from various centers that indicate a strong role for robotics in the future of urology, surgery, and general medicine. Robotic technology is progressing on every level and will continue to be a driving force in the progress of science and medicine.

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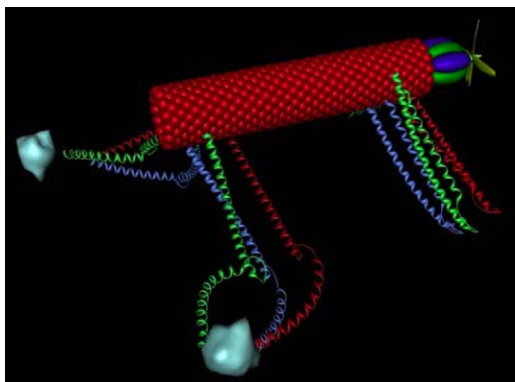


Fig. 7. A protein- and DNA-based nanorobot. (Courtesy of Rutgers University, New Brunswick, New Jersey; with permission.)

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# Robotics technology: a journey into the future

Abhilash Pandya, PhD\*, Gregory Auner, PhD

*Department of Electrical and Computer Engineering, Wayne State University, Engineering Building #3160,  
5050 Anthony Wayne Drive, Detroit, MI 48201, USA*

The authors predict that technology-assisted medicine, and robotics in particular, will have a significant impact over the next few decades. Robots will augment the surgeon's motor performance, diagnosis capability, and senses with haptics (feel), augmented reality (sight), and ultrasound (sound). Robots already boost surgical skills by filtering tremor and scaling motions, but may be able to automate certain routine tasks to free the surgeon to focus on higher-level tasks. With intelligent interfaces, the robotic system could warn surgeons of incorrect trajectories or restrict the movements of the surgery away from dangerous or critical areas. The authors predict that the impact of robots will parallel that of imaging technology in medicine today.

Robotic devices have been used in cardiac surgery [1–13], urology [14–16], fetal surgery [17,18], pediatrics [19–22], neurosurgery [23,24], orthopedics [25,26], and many other medical disciplines. As with imaging technology, robotics will bring patient care and treatment a leap forward. In several cases, it has started to happen already. In particular, the Vattikuti Urology Institute at Henry Ford Hospital in Detroit, Michigan is the first facility in the country to perform surgery routinely using a robotic system for the treatment of prostate cancer. With this robotic laparoscopic procedure, the patient's pain, blood loss, and recovery time in the hospital and at home are reduced significantly compared with traditional surgery. In addition, the procedure eliminates the need for large incisions [15].

Even with enormous technologic gains, robotic surgery is still in its infancy. Some major technologic improvements are needed for this technology to reach its ultimate potential, including better visualization, tactile sensing, diagnostic sensing, and miniaturization [27]. This article gives the authors' vision of the future of robotic technology with respect to robotic vision, sensor fusion, and nano-/microrobot development and discusses the path to that future from the current state-of-the-art for medical robots.

## **Robotic vision (augmented reality and image guidance)**

Many studies have compared and improved the surgical interface and improved the surgeon's performance [28–31]. One of the key problems of robotic surgery, however, is that surgeries can become more difficult and take longer [32]. In robotic surgery, the magnification and, therefore, the size of the field-of-view changes with the proximity of the endoscope to the objects being viewed [33]. Because of the small incisions and camera view, the surgeon can no longer see inside the patient directly. Visualization is critical for systems that use a robotic interface because the surgeon typically operates from a remote location and relies almost entirely on indirect, limited field-of-view video of the surgery [27,33,34]. Direct linkage of medical robotic systems to patient data and the optimal visualization of those data for the surgical team are important for successful operations.

In their review article on medical robots, Cleary and Nguyen [27] state that if medical robots are to reach their full potential, they need to be more integrated systems in which the robots are linked to the imaging modalities or directly to

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\* Corresponding author.

E-mail address: [apandya@ece.eng.wayne.edu](mailto:apandya@ece.eng.wayne.edu)  
(A. Pandya).

the patient anatomy. They state further that robotics systems need to be developed in an “Image-Compatible” way. Visual information from the patient site needs to be augmented to allow greater situational awareness, accuracy, and confidence. That is, these systems must operate within the constraints of various image modalities such as CT and MRI. This link, they conjecture, is essential if the potential advantages of robots are to be realized in the medical domain.

In addition, surgical planning and information management for these robotic systems is essential for successful operations [27]. Two main problems encountered in robotic surgery are nonoptimal port (incisions on the patient’s body for the robotic arms) placements and robotic-arm collisions. Robotic-arm collisions often require manual repositioning of the robotic arms on the operating table that unnecessarily adds to the operative time. Incorrect port placement typically results in robotic-arm collisions, can damage robotic instruments, and also can make the operative site inaccessible. Improved accessibility to the operative site can enhance patient safety [35]. These problems can be avoided in the preoperative stages given the appropriate visualization tools. Therefore, it is important that a robust visualization system be built that is linked to patient imaging data to offer the surgeon tools for visualization, robotic system setup, and port placement [36].

Computer modeling tools that help visualize the anatomic structures of the patient would aid the surgeon greatly in the preoperative stage. Visualization tools can help the surgeon determine optimal port-placement sites. In addition, these tools will help determine the placement of the

robotic arms on the operating table to avoid collisions between arms during the procedure and maximize the range of motion of the instruments. A significant potential exists to affect medical robotics with the preoperative planning and intraoperative visualization tools [37].

Two types of visualization technology have been used for real-time visualization in the medical domain: augmented reality (AR) and virtual reality (VR) [38,39]. These visualization methods are well suited for robotic surgery. Image guidance is an example of VR. In image-guidance surgery (IGS), the surgeon views a computer-generated world of image data and three-dimensional models after registration. The registration ensures a one-to-one correspondence to the end-effector of the robot and the image coordinates. In contrast, the AR system generates a composite view for the user that includes the live video view fused (registered) with either precomputed data (eg, three-dimensional geometry) or other registered sensed data [40]. AR is a variation and extension of VR and represents a middle ground between computer graphics in a completely synthetically generated world (as in VR) and a normal camera view of the real world [41–45]. The current technique of image guidance does not allow the surgeon to use real and synthetic data simultaneously [46]. The surgeon can detect anomalies using advanced imaging and sensors and can place his or her tools accurately within surgical environments with robots. Nevertheless, the surgeon also needs his or her own vision to detect other features that may not be available from the sensor information. This, the authors believe, is one advantage of AR (Fig. 1) [47].

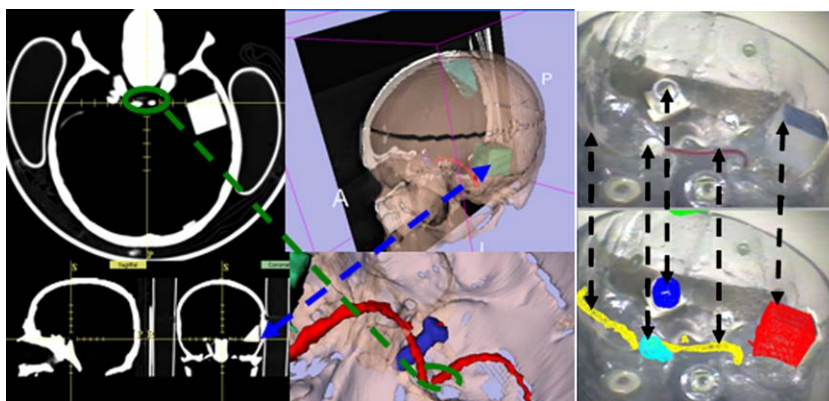


Fig. 1. Augmented reality and image-guided visualization.

## Robotic ultrasound

Imagine listening to tissue for abnormalities. New technology using acoustic holography is within reach for early diagnosis of diseases such as cancer because of significant advances in microsystem and signal analysis. Although holography technology has existed for over 25 years, its application in the clinical/diagnostic arena did not come to fruition because of a lack of advanced microsystems and signal analysis technology. What has been missing is a conversion element that can record the ultrasound interference patterns, reconstruct them with a real or synthesized ultrasound interference pattern, and finally reconstruct them with real or synthesized ultrasound frequency waves that could be transformed directly into a visible image.

This is now possible using micropiezoelectric arrays equipped with chip reconstruction at high spatial and temporal resolution. In addition to three-dimensional holography imaging, a vital objective of the device is to recover the wave envelope emerging from each pixel. Although the hologram requires freezing the waves in time long enough to capture a stable interference pattern with adequate signal-to-noise (typically 10 microseconds), the wave envelope contains an instantaneous integrated dynamic history of the scattering events along each ray path throughout the

volume. If this information is extracted, the physical parameters of each resolvable volume element (ie, approximately  $1 \text{ mm}^3$ ) in the insonified volume then should enable diagnosis of the nature of the material. In principle, it is possible to distinguish small tumors from healthy tissues by this method. Preliminary images and phase information are shown in Fig. 2.

## Robotic touch

Can the sense of hyper-touch and -temperature be useful for a surgeon? Development of advanced force-sensing arrays can advance tactile augmentation on the robot. For example, new dual-mode acoustic wave sensors that can switch between surface acoustic wave and surface transverse wave modes can sense pressure and viscosity in liquid, distinguish force caused by liquid or solid interactions, and further distinguish between normal and transverse forces (pinching pressure or sliding frictional forces). Because new wide-bandgap, semiconductor-based acoustic sensor arrays have linear temperature coefficients, they can be superb temperature sensors as well. Thus, tactile forces and sensory information on touch and temperature can mimic human tactile feeling but with many orders of magnitude greater sensitivity and precision.

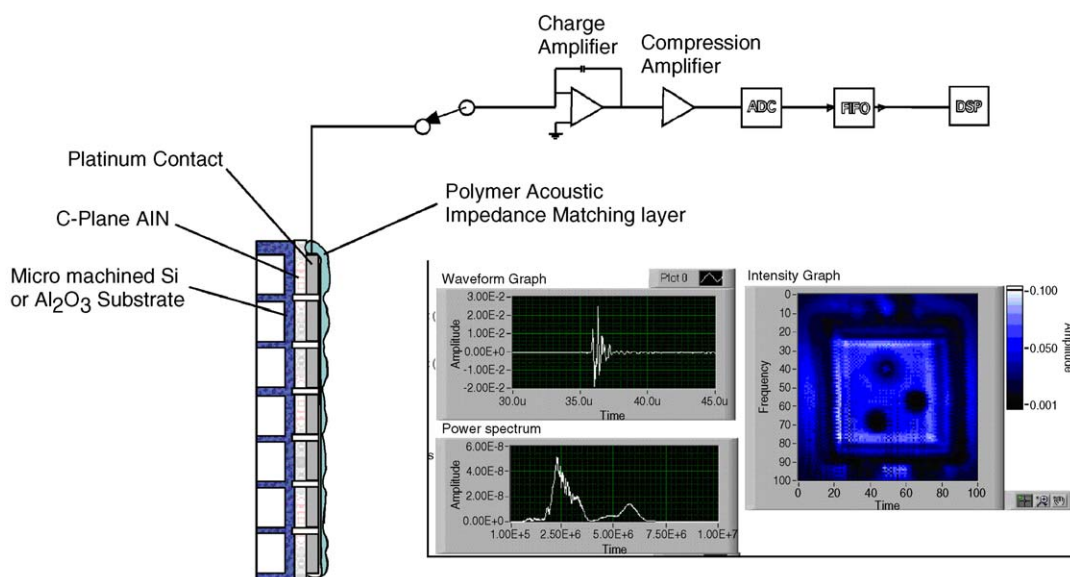


Fig. 2. Holographic image created from ultrasound signals.

## Diagnostic sensors

The authors believe sensing systems will benefit robots most in the area of diagnostic sensing. Sensors that can differentiate in real-time between various pathologic conditions, such as cancer, and normal tissue would be invaluable. One such sensor is a micro-Raman probe, which may be able to be mounted on the end-effector of a robotic device to provide pathologic evaluation.

Cancer treatment, whether with drugs, radiation, or surgery, depends on distinguishing malignant from normal tissue. Visual inspection is seldom adequate for this task. Biopsy with histologic evaluation is the criterion standard for making this determination. Final results usually require at least 12 to 24 hours, however, and even the more immediate frozen section generally requires at least 20 minutes from when the tissue is removed until an answer is available. The process of evaluating all essential margins and surfaces can be time-consuming and prone to sampling errors. As the ability to treat cancer improves, the early detection of disease provides an even greater opportunity for intervention resulting in a significant increase in survival.

Raman spectroscopy is a vibrational spectroscopic technique that originates from inelastic scattering of light by vibrating molecules. This

provides detailed information about the bimolecular composition of tissues that may be used to distinguish between normal and malignant tissues. Raman spectroscopy has been under investigation during the last decade because of its potential application as a molecular-level tool for the diagnosis of cancer [48].

Pathologic conditions involve changes in molecular composition of tissue as a result or cause of disease. By measuring Raman-marker bands of proteins, lipids, or nucleotides, the relative ratios and absolute concentration of each component can be determined and related to pathologic changes. Raman spectroscopy could enable in vivo detection of these changes in a minimally invasive, nondestructive manner by using the appropriate excitation laser wavelength and laser power. The Raman spectral data obtained then could be used to guide further clinical action. The importance of Raman spectroscopy lies in its potential in vivo application and direct, real-time therapeutic intervention based on that information (Fig. 3).

Micro-Raman probes can be built to be miniature systems specific to a particular pathology. The authors envision that future robotic system will have on-board sensor systems that include diagnostics capability. These robots will be able to work methodically and perhaps

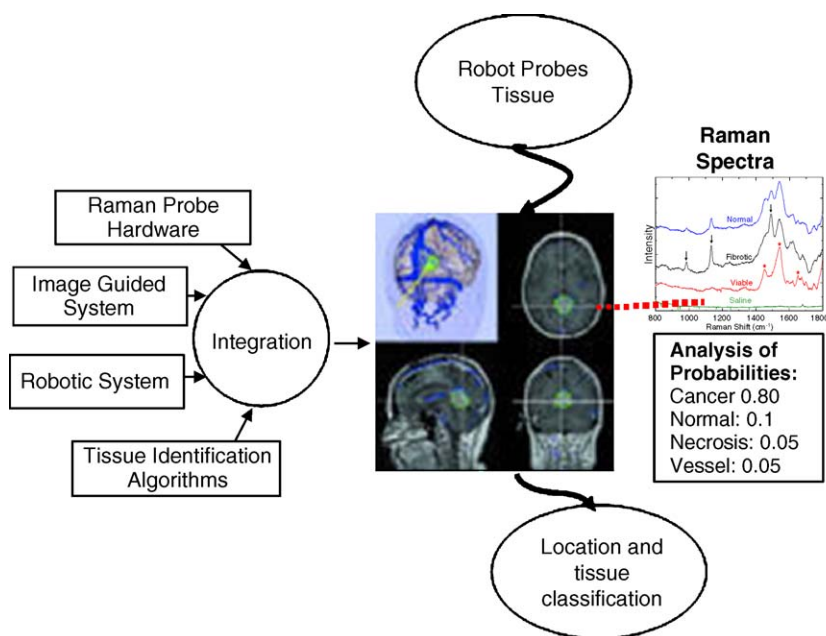


Fig. 3. Integration of a micro-Raman sensor with a robotic system.

autonomously to remove tissue that they determine to be diseased.

### Future micro- and nanorobots

Autonomous robots need to be miniature. *Nanotechnology* can be defined as structures and mechanism that extend below 100 nm in size. “In nature, nano-scale structures and mechanisms are ubiquitous,” Richard Feynman [49] states in his pioneering lecture on nanotechnology. “Nature transforms inexpensive, abundant and inanimate ingredients into self-repairing, self-aware creatures that walk, wiggle, swim sniff, see think and even dream.” Feynman poses the question, “What could we humans do if we could assemble the basic ingredients of the material world with a glint of nature’s virtuosity?”

DNA can be considered biologic nanosoft-ware. For instance, ribosomes can be considered large-scale molecular constructors/robots [50]. Enzymes are nature’s truly functional molecular-sized assemblers. Genetic engineers are not creating new tools per se, but adapting and improvising from those nature has provided. Future generations of engineers, armed with molecular-engineering techniques, will have a real chance of imitating and improving on nature.

One of the most amazing nanomachines found in nature is the DNA polymerase. When DNA is replicated or copied, it has to be copied exactly, otherwise minor errors in the copying process lead to major problems in the creation of the structures of the cells. DNA polymerase is an accurate machine. It creates an exact copy of DNA each time, making less than one mistake in 1 billion bases. DNA polymerase plays the central role in the processes of life. It carries the weighty responsibility of duplicating our genetic information. It is a sophisticated machine that has numerous regions, each responsible for various functions. For instance, one section of the “machine” is used for synthesis, another for proof-reading, and a third for removal of sequences (Fig. 4).

Nano- or microelectro mechanical systems are multidisciplinary fields. They involve solid-state electrical engineers studying the electrical properties of nanostructures, mechanical engineers studying the physical properties of nanostructures, and genetic engineers who have created methods to study important nanomachines in nature. This section focuses on two avenues of

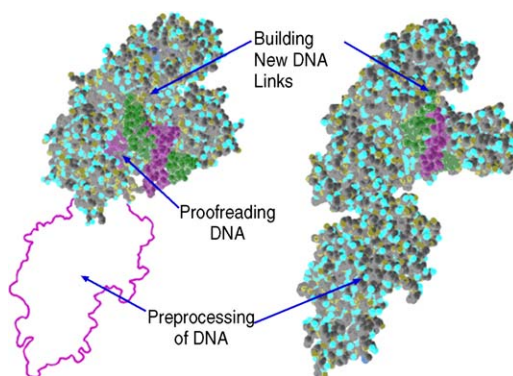


Fig. 4. Polymerase (nanomachine) used to duplicate DNA.

research: (1) the solid-state engineering efforts to use DNA to build nanostructures from DNA molecules and (2) the genetic engineering efforts to describe the three-dimensional structure and function of molecular machines.

The authors try to give a greater understanding of the use of one of nature’s most important molecules, DNA, in the field of nanotechnology. DNA in nature functions as an information molecule [50]. It is a “computer program” that dictates what molecular structures should be built, how the molecular machines should function, and ultimately, how a living organism should behave. DNA’s amazing properties allow it to be used for fabrication of nanostructures. This section focuses on DNA and its potential use for nanotechnology. It also provides some ideas for the future imitation of nature for building synthetic/organic hybrid nanomachinery.

Nature clearly has built functional nanomachines. The key to Nature’s development is its special software: DNA. DNA’s biologic importance lies in the specificity of the base pairing that holds the two strands of the double helix together: adenine pairs with thymine and guanine pairs with cytosine. The structure that results from these complementary interactions is a linear molecule; that is, it is not branched. By designing appropriate sequences, however, it is possible in synthetic systems to produce branched DNA molecules.

DNA is well known for duplication and storage of genetic information in biology. It also has been shown recently to be highly useful as an engineering material for construction of special-purpose computers and micron-scale objects with nanometer-scale feature resolution [51,52]. Properly designed synthetic DNA can be a

programmable glue that, through specific hybridization of complementary sequences, will self-organize reliably to form desired structures and superstructures. Such engineered structures are inherently information-rich and are suitable for use directly as computers or as templates for imposing specific patterns on various other materials.

In theory, DNA can be used to create any desired pattern in two or three dimensions and simultaneously to guide the assembly of a wide variety of other materials into any desired patterned structure. Given the diverse mechanical, chemical, catalytic, and electronic properties of these specifically patterned materials, DNA self-assembly techniques hold great promise for bottom-up nanofabrication in many applications in wide-ranging fields of technology as diverse as electronics, combinatorial chemistry, nanorobotics, and gene therapy.

The structures and arrays described here are static structures. Can a nanomechanical device be produced from DNA? Seeman and LaBean [51,52] describe a minimal mechanical device using the DNA molecule. This molecule's structure switches between two alternatives in response to an external signal. Seeman's group has developed a two-state device predicated on the B to Z transition of DNA. Conventional DNA, known as *B-DNA*, is a right-handed molecule. There is another structure of DNA that is radically different from B-DNA, however, known as *Z-DNA* [19]. Z-DNA is a left-handed molecule. Seeman and LaBean produced a two-state mechanical device (like a pincer) using a combination of B-DNA and Z-DNA [19]. The two states are well defined structurally and controllable. Although these steps are significant, they are the first steps in the evolution of nanorobotic devices.

The unique features of DNA allow it to be used as a building block to create other new, basic structures from which complex machines can be built. DNA nanotechnology also can be combined with carbon nanotubes to take advantage of the self-organization properties of DNA. The authors conjecture that the future will yield controllable nano- and microrobots that can be used for medical use for surveillance and perhaps treatment.

### How can we get there

As robots become more autonomous and the surgeries they can assist in performing become more complex, the authors envision a merging of

sensors with robots. Systems such as pressure sensors, tactile sensors, and temperature sensors no doubt will become more advanced and will allow the surgeon to perform more delicate surgeries. In addition, video sensing and imaging sensors will become integrated into robot end-effectors, which will give an unprecedented view of the human body in real-time.

Although robots have the potential to improve the precision and capabilities of physicians, the number of robots in clinical use is still small. First, there needs to be a strong cooperation between engineers and clinicians. Engineers need to team with clinicians and biologic scientists to understand their needs and build useful and simple systems. Building is not enough, however; these systems need to be tested by surgeons to ensure that the performance is affected positively and that the patient's outcome is enhanced. Clinical trials need to be well organized with results quantified. Only then will the medical community accept these systems.

The merging of sensors with robots is a logical step. Sensors of touch and temperature to enhance the surgeon's haptic sense, imaging sensors to allow greater visualization, and sensors for diagnostics can be more effective when used in conjunction with robotic devices.

In the realm of nanotechnology, the authors believe that the future will meld two disciplines: nanotechnology and molecular biology. Molecular biologists have seen and studied what is possible in the nanotechnology world—they just don't know how to build these systems. Nanotechnologist can work on these scales and are starting to understand how molecular machines work, but some are unaware of what nature has built already. Can DNA be synthesized in a laboratory so that it can carry out assembly instructions for molecular building designed by researchers? The robots or machines of this scale could be used to clean vessels, deliver drugs to specific locations, and seek out and destroy particular types of cells.

In summary, a melding of engineers and surgeons, a melding of sensors and robots, and a melding of nanotechnologists with microbiologists are needed for this field to progress.

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